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MODELLING CHANGE IN THE LOWLAND HEATHLANDS OF DORSET

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A thesis submitted for the degree of Doctor of Philosophy

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September 1999

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE

GEOGRAPHY

Doctor of Philosophy

MODELLING CHANGE IN THE LOWLAND HEATHLANDS OF DORSET

by Abigail M. Nolan

A geographical information system (GIS) and regression were used to model vegetation changes that have occurred in the lowland heaths of Dorset, England between 1978 and 1996. This research contributes to the field of landscape ecology by producing succinct models of the spatial dynamics of dwarf shrub vegetation at two scales (patch and pixel). This research also examines whether the much hypothesised relationships between change and patch geometry, edge effects, isolation, context and the attributes of a patch including the areal extent (and density) of vegetation types in a fragmented environment exist, and models the process of succession spatially. Further, the effectiveness of management practices in controlling the process of succession was analysed.

Extensive information was available from complete surveys of the heathlands of Dorset carried out by the Institute for Terrestrial Ecology (ITE) in 1978, 1987 and 1996 in which the heathlands were divided into 200 m by 200 m pixels. Vegetation change was examined initially on a patch-basis. The patches were created by amalgamating cells containing any area of heathland (dry heath, wet heath, humid heath and peatland) in 1978. The patches were used as a template for the 1987 and 1996 data. An analysis of areal change indicated that three processes appeared to result in vegetation change. These were land use change, succession and management. A statistical model of heathland dynamics was produced to represent the relationship between percentage change in area of dwarf shrub vegetation and several explanatory variables. The explanatory variables were selected based on current understanding of dwarf shrub vegetation dynamics in a fragmented environment and which were most likely to influence the process of succession. They included patch geometry, context (provided by a remotely sensed Landsat TM image), edge effects and the areal extent (and density) of dwarf shrub vegetation and invasive species types.

The patch-based model indicated that two main variables influenced change in dwarf shrub vegetation to decline. First, the *density* of dwarf shrub vegetation in a patch and second, the *area* of invasive species in a patch. Further, it appeared that management arrested the process of succession in some cases and caused the area of dwarf shrub vegetation to increase in 'others'. The pixel-based analysis did not result in any significant relationships which questions the scale of the analysis, and the signal-to-noise ratio of the data.

This research examined the process of succession spatially by modelling the spatial dynamics of the dwarf shrub vegetation of Dorset. The analysis provided insight into the spatial process of change. To prevent further losses in area of dwarf shrub vegetation fragmentation of the remaining area of dwarf shrub vegetation must be prevented, to prevent further fragmentation the area of invasive species in a patch must be reduced.

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Acknowledgements

I would like to acknowledge the assistance of the following individuals and organisations.

I thank my supervisors Dr Peter Atkinson and Dr James Bullock without whose constant support, enthusiasm and direction this thesis would not have been completed.

I would like to extend sincere thanks to Dr Nigel Webb, Mr Rob Rose, Mr Ralph Clark and all the staff of the Institute of Terrestrial Ecology, Furzebrook Research Station. Many thanks also to the many individuals and organisations who volunteered management data. In particular, H. Army of English Nature, all the staff of the British Herpetological Conservation Trust, and the RSPB and L. Haskins and R. Brunt of the Dorset WildlifeTrust.

Within the Department of Geography, University of Southampton, I would particularly like to thank Dr. Jim Milne who strived valiantly to answer (with great wit!) my never ending stream of questions. Thanks also to Dr Charles Kerr and Dr David Martin for many useful suggestions and much sound advice. Many thanks also to all the administrative staff and Departmental secretaries. I would also like to acknowledge the assistance and support of all the staff in the Cartographic Unit.

Many collegues and friends have contributed time and energy to the production of this thesis. I would especially like to thank Robin Jackson, Toby Wicks and Suha Berberoglou for all their help over the past few years.

Finally, I would like to thank all my family and friends, in particular, Bec and Owen for keeping me sane. I am most grateful to Rosie, Alison, Pip, Rich M., Robin. E., J-B, Fred, Sab, Sally and Alan without whom life would have been very dull. I will forever be indebted to James for managing to live with me without murdering me and to Mega Tom for feeding me and without whose constant distractions I would have submitted years earlier. I am especially grateful to my family: Op my bestest drinking buddy, Luke for his selfless manning of the 'suicide watch', Danny for never ringing me, Kate for being 'nice', Damian (Y) for frequently grunting at me, Mary for being mad and my parents for their unwavering support and numerous lunches.

Abbreviations

BOD-DO	Biological Oxygen Demand and Deficit of Oxygen
DERC	Dorset Environmental Records Centre
DWT	Dorset Wildlife Trust
EMR	Electro Magnetic radiation
EN	English Nature
GCP	Ground Control Point
GIS	Geographical Information System
ITE	Institute for Terrestrial Ecology
LAI	Leaf Area Index
MSS	Multi-spectral Scanner
NT	National Trust
RMS	Root Mean Square
RSPB	Royal Society for the Protection of Birds
SSSI	Site of Special Scientific Interest
TIR	Thermal Infrared
TM	Thematic Mapper

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter introduces an analysis of change in a fragmented heathland environment. It begins by discussing the lowland heathland of Dorset, southern England. The processes causing change, the factors affecting these processes of change over time and the scale of the analysis of change in heathlands are examined. The modelling process is also introduced. Finally, the structure of the thesis is defined chapter by chapter to illustrate the premise under which each part of the research was undertaken. This research contributes to the field of landscape ecology in three ways. First, by producing a succinct model of the spatial dynamics of dwarf shrub vegetation at two scales (patch and pixel). Second, by testing the (much) hypothesised relationships between change and patch geometry, edge effects, isolation, context and the attributes of a patch including the areal extent (and density) of vegetation types in a fragmented environment. Third, by modelling the process of succession spatially. In addition, the effectiveness of management practices in controlling the process of succession was analysed.

1.2 The lowland heathlands of Dorset

The lowland heathlands of Dorset were created in the Mesolithic period when humans felled the forest and allowed animals to graze, preventing the re-establishment of the climax vegetation. Traditional management practices (grazing, cutting and burning) maintained the heathlands until the latter half of the twentieth century. Such practices delayed succession of the heathlands to woodland and their decline resulted in loss of heathland. This process, combined with increased urbanisation, an increase in agricultural conversion and forestry plantations, caused considerable fragmentation.

Lowland heathlands are characterised by low species diversity. Heathlands, such as those in Dorset, tend to be dominated by dwarf shrub vegetation, particularly ericoids: heather (*Calluna vulargris*), cross-leaved heath (*Erica tetralix*) and bell heather (*Erica cinerea*). The Dorset heathlands provide a habitat for many species of conservation importance such as the Dartford warbler (*Sylvia undata*), sand lizard (*Lacerta agilis*), smooth snake (*Coronella* *austriiaca*) and marsh gentian (*Gentiana pneumonanthe*) (Webb and Haskins, 1980). Further, these heaths are now the only place in Britain where all six of this country's native reptiles co-exist. However, much of the heathland in Dorset has been lost over the last century and a half. The heathlands that survived are fragmented and this has increased the likelihood of further losses of heathland and the biota that the heaths support (Moore, 1962). Haskins (1978) calculated, from Isaac Taylor's maps of Hampshire and Dorset, that around 39,960 ha of heathland existed in Dorset between 1759 and 1765. By 1987 only 5,141 ha of heathland remained in a much fragmented state (Webb, 1990). It is because so little of the Dorset heathlands remain and because of the rare communities and species that the heathlands support that they are now a top priority for habitat conservation in Britain (Biodiversity Steering Group, 1995). Therefore, there is an urgent need to quantify the problem of fragmentation of the heathlands of Dorset by developing more sophisticated, models of change in heathlands. Such models will be invaluable to heathland managers.

1.3 The processes at work in a fragmented heathland environment

The use of traditional heathland management practices declined over the period analysed in this thesis (between 1978 and 1996) led to increased pressure from succession. However, succession was not the sole cause of change. Changing land use (urbanisation, forestry and agriculture) also resulted in losses of heathland area. Both processes served to fragment the heathlands of Dorset.

Heathland succession involves invasion by scrub, carr (wet scrub vegetation) and woodland species. Therefore, the area of invasive species in a fragment and surrounding a fragment, is an important component in the process of succession. Webb and Hopkins (1984) state that 'isolated patches of heathland differ from many other habitat islands because they are usually surrounded by communities which are richer in species than the islands themselves and, thus, there may be continual pressure from colonisation and succession'. The fragments of heathland which remain tend to be isolated patches lying in a matrix of forest, agricultural and urban land and are, therefore, likely to be under considerable pressure from succession. Land use change on the other hand, is not a function of spatial context (in this analysis). Land use change cannot be predicted readily as it does not depend on the composition of an area of heathland fragment. Changing land use remained largely unregulated until the late 1980s, when legislation was introduced to protect the heathlands.

Since the 1980s, a third process has also caused change tending to protect the area of heathland over time. This process is heathland management. An aim of management is to maintain heathland by providing a mosaic of different age stands and thereby a range of habitats.

In all, there are three main processes in action in the heathlands of Dorset, one natural, ecological process which is succession and two anthropogenic processes which are land use change and management. Succession is the process of change of primary interest in this research. It is anticipated that the influence of the factors affecting succession on process of landscape change can be identified.

1.4 The spatial process of fragmentation

The fragments which constitute the Dorset heathlands are remnant patches isolated initially by disturbance of the surrounding area (Forman and Godron, 1986). Important attributes of such fragments include the scale of fragmentation, context, degree of isolation, fragment size and shape, species distribution (both areal extent and density) and edge effects (Lord and Norton, 1990). A fragment's surroundings may influence its chances of survival (Dunning, 1992; Webb, 1992; Webb *et al.*, 1984). A heathland fragment surrounded by scrub or woodland may be under continual pressure from succession. A fragment surrounded by houses is under no such pressure although other processes may cause problems (for example, anthropogenic activity, wild fire and limited in-migration of heathland species). The size (Moore, 1962), shape and perimeter length of a fragment may all influence the rate of change (Baskent & Jordan, 1995; LaGro, 1991; Rex & Malanson, 1990). Larger fragments of heathland may be more resistant to change as are more rounded fragments, with long thin fragments (large perimeters) less so. If the rate of succession across a fragment is uniform, then a long thin fragment will be invaded more quickly than a large round patch (if succession comes from the edge). From ecological literature it was clear that greater areas of scrub, carr or woodland in a fragment or in the edge of a fragment, lead to greater pressure from succession due in part to species dispersal (in this case, invasive species). It is most likely that pressure from succession in exerted from outside a fragment or from the edges (Fagan *et al.*, 1999; Lavers & Haines-Young, 1993; Wilcove *et al.*, 1986; Webb & Hopkins, 1984). The converse is also true: greater densities of heathland species may imply that a patch is not fragmented and, therefore, is less easily invaded.

Overall, the influence of the spatial geometry of a fragment, context, area of invasive species in a fragment or in the edge of a fragment on the process of succession, can provide insight into the spatial process of fragmentation in the heathlands of Dorset.

1.5 The scale of fragmentation

A patch (fragment) is the most obvious natural ecological unit of a lowland heathland environment. Therefore, change was examined initially on a per-patch basis as fragmentation appeared to occur at a patch scale. However, within a landscape different patches may experience ecological change at different rates, creating complex patterns of change (di Castri & Hadley, 1988). Patches are themselves patchy, that is change may also occur at a sub-patch level. If change was occurring in the heathlands of Dorset at a sub-patch level, then the most obvious choice of scale for further analysis was the pixel scale. The heathlands were surveyed on a 200 m by 200 m pixel basis. Although a pixel is not an obvious choice of ecological unit, the data limited the choice of scale for a sub-patch analysis of the process of fragmentation. Therefore, two analyses were carried out, a per-patch analysis followed by a per-pixel analysis of change in the heathland of Dorset.

1.6 Modelling fragmentation

Previous analyses indicated that fragmentation of the heathlands of Dorset was occurring at an increasing rate, resulting in losses of heathland vegetation. The processes which resulted in such change were identified (succession, land use change and management) through close examination of the ecological literature (see Chapter 2, 2.2). Further, attributes which affected the process of succession were identified and the scale of the analysis of fragmentation established. The next step was to isolate patterns of change with the aim of modelling them. If the process of change can be understood through the influence of several variables on the rate of change, then change can be managed more effectively. Obviously, change due to anthropogenic activity (land use change) could not be predicted in such a way.

The model building process aimed to quantify how variables such as patch size and patch shape, context and area (and density) of both heath and invasive species affected the rate of change in area of heathland over time. Percentage change rather than areal change in area of heathland was the chosen response variable. Percentage change was examined at a patch scale but also a pixel scale. Therefore, the explanatory variables altered between the analyses. For example, indices of patch geometry no longer applied to pixels and patch edge effects were examined with reference to the distance a pixel lay from the edge.

Once the model building process had been identified, a suitable model was chosen. There are many types of spatial ecological modelling (Czárán & Bartha, 1991), but few models have been developed for ecological processes identifiable at the landscape (patch) scale (for example, Dunning *et al.,* 1992). Regression was chosen as it is a simple technique commonly used in ecology. Regression (both simple and multiple) provided the basis for building a predictive statistical model of the spatial dynamics of the heathlands of Dorset. Percentage change was examined at an 'aggregated primary' category level (percentage change in area of heathland) and at a 'primary category' level (percentage change in area of dry heath, wet heath, humid heath and peatland) using regression. Further, percentage change was examined at the 'secondary category' level. The relationship between percentage change in area of dwarf shrub vegetation (and dwarf shrub vegetation type) and individual invasive species was examined. The influence of current management practices was also examined.

1.7 Summary and statement of objective

Heathlands are plagio-climax communities in a state of arrested succession. Left to their own devices they will revert to their climax vegetation: woodland. The heathlands of Dorset are no different. The area of heathland has been progressively reduced in extent due to urbanisation, forestry plantations, agricultural practices and the decline in traditional heathland management practices which prevented the heathlands reverting to woodlands. These anthropogenic influences combined with succession have resulted in the fragmentation of the heathlands. Anthropogenic influences cannot be readily predicted, but succession can. Therefore, the overall aim of this thesis is to isolate the factors affecting the rate of succession (correlations analysis) and quantify their influence on percentage change in area of heathland using regression modelling. The analysis is undertaken at a patch and a sub-patch (pixel) level. The models should provide insight into the spatial dynamics of the lowland heathland of Dorset and provide a succinct set of guidelines for heathland managers.

1.8 Thesis structure

Chapter 1 has introduced the basic research context and aim. *Chapter 2* reviews relevant literature, including a detailed description of heathlands in general and an outline of the historical development and classification of the Dorset heathlands. A discussion is provided on the process of succession, the factors which affect this process and the influence of management on the heathland. *Chapter 3* outlines the study site and the procedures taken to acquire and enter the data into a Geographical Information System (GIS). *Chapter 4* is concerned with modelling at the patch level. Initially, only decreases in area of heathland were examined as the focus of interest was succession. Regression was used to identify significant relationships between percentage change (decreases) and several explanatory variables. *Chapter 5* is concerned with modelling change in the heathlands on a per-pixel basis. *Chapter 6* uses regression to analyse the effects of management on percentage change in area of heathland at both the patch and pixel level. The relationship between percentage increases and management was examined initially. However, percentage decreases were also included in the analysis. *Chapter 7* is a discussion of the patch- and pixel-based analyses as well as the implications of the findings for the heathlands of Dorset. *Chapter 8* concludes the thesis by summarising the research findings and pointing out their implications for heathland conservation. It also identifies research avenues which require further investigation in the light of the research presented in this thesis.

CHAPTER 2

HEATHLAND ECOLOGY

2.1 Introduction

A thorough review of the literature relating to heathlands, their development and, in particular, the study site, that is, the lowland heathlands of Dorset, southern England, is presented here. Historical factors which have determined the basic composition of these heathlands are outlined before proceeding to a more detailed description of the nature of these heathlands. The fragmentation of the heathlands is also examined as are their management and conservation. Literature outlining the basics of ecological modelling from its conception, through to the main kinds of ecological model used today, is reviewed with particular emphasis on statistical regression models as these are the foundation upon which this research is based.

2.2 Historical development of heathlands

Heathland vegetation dominated by dwarf ericoid shrubs extends over 25° of latitude, from northern Spain to beyond the Arctic Circle on the west coast of Norway, and east of Poland, with the greatest concentrations of heathland to be found in the countries bordering the North Sea. Lowland British heathlands are part of the western Atlantic alliance (Noirfalise & Vanesse, 1976). They are mainly concentrated in clusters in Cornwall, Devon, Dorset, Hampshire, Surrey, Suffolk and Norfolk. Today, only around one sixth of the area of lowland heath (as opposed to upland heath or moorland) that existed in 1800 remains (Michael, 1992). Within Britain today, lowland heathlands are rather restricted because of increased agriculture and urbanisation.

Lowland heathland landscapes are in general, semi-natural resulting from, and being maintained by, human activity. Heathlands originated during the Mesolithic period when deforestation first began. The removal of the forests allowed wild animals to graze preventing the re-establishment of the climax vegetation and allowing the establishment of dwarf ericoid shrubs. Evidence for this is provided from the pollen analyses carried out by Dimbleby (1962) on 32 sites around Britain. The major deforestation of Britain did not begin until later in the Neolithic or Bronze Age.

Heathlands exist on sands, gravels (in some cases glacially deposited), or acidic soils (pH in the range 3.5 to 6.7) that are low in fertility and nutrients, notably nitrogen and phosphorus, where there are no excessive fluctuations in humidity and, perhaps most importantly, where there are factors that arrest the natural succession to woodland
(Webb & Haskins, 1980).

2.2.1 Defining heathlands

It is not easy to impose a precise definition on the word *heathland,* which relates more to a characteristic type of landscape than to its vegetation and fauna (Gimingham, 1992), and yet many authors have attempted to classify heathlands (both upland and lowland) for their own research. For example, Specht (1979) defined heathlands as vegetation dominated by dwarf shrubs, notably heather (*Calluna vulgaris*), cross-leaved heath (*Erica tetralix*) and bell heather (*Erica cinerea).* Webb (1990) described heathlands as a plagioclimax community dependent on man-induced activities to maintain dwarf-shrub vegetation and to prevent secondary succession to woodland and as characterised by low diversity of species, with high dominance achieved by a few. The National Vegetation Classification defined heathlands as vegetation types in which sub-shrubs play the most important rôle, sometimes in a dwarfed or broken canopy, with such species as *Calluna vulgaris* and other ericoids, *Vaccinium, Empetrum* and *Ulex minor* and *Ulex gallii* usually dominating either alone or in various combinations (Rodwell, 1992). Therefore, heathlands can be defined in general terms as vegetation dominated by dwarf shrubs, in particular, species of *Erica* and *Calluna.*

The Dorset heathlands can be classified as Atlantic but contain elements of both Armorican heathland, chiefly characterised by bell heather (*Erica cinerea),* Dorset heath (*Erica ciliaris*) and western gorse (*Ulex gallii),* and Anglo-Norman heathland, in which bell heather (*Erica cinerea*) and dwarf gorse (*Ulex minor*) are the dominant species (Noirfalise & Vanesse, 1976). For the most part, the vegetation of the Dorset heathlands (Rodwell, 1992) corresponds to the following National Vegetation Classification categories:

1. H2, *Calluna vulgaris - Ulex minor* heathland (heather and dwarf-gorse heathland). This heathland type is found on freely drained, nutrient-poor acidic soils in eastern Dorset. Bell heather (*Erica cinerea*) and dwarf gorse (*Ulex minor*) are intimately mixed with heather, and wavy hair-grass (*Deschampsia flexuosa*) is prominent.

2. H3, *Ulex minor - Agrostis curtisii* heathland (dwarf gorse and bristle-bent heathland). This heathland type is found where soils are less well drained and the climate is oceanic (Dorset). *Agrostis curtisii* (bristle-bent grass) is the most regular component along with heather and dwarf gorse. *Erica tetralix* (cross-leaved heath) and *Molinia caerulea* (purple moor-grass) are also quite prominent.

3. H4, *Ulex gallii - Agrostis curtisii* heathland (western gorse and bristle-bent heathland). This heathland is characteristic of moist, acidic soils and a warm oceanic climate. It, therefore, replaces H3 in western Dorset. It is similar to H3 except that *Ulex gallii* (western gorse) replaces *Ulex minor* (dwarf gorse). The boundary between the two species is remarkably sharp.

4. M16, *Erica tetralix - Sphagnum compactum* heathland (cross-leaved heathland and *Sphagnum* wet heathland). This is confined to acidic, oligotrophic mineral soils where drainage is impeded or there is peat. It is a transitional habitat between drier heathlands and sphagnum bogs. *Gentiana pneumonanthe* (marsh gentian) and *Erica ciliaris* (Dorset heath) grow and *Erica tetralix* (cross-leaved heath) and *Molinia caerulea* (purple moor-grass) are the predominant vascular plants.

The research in this thesis was based upon the Dorset Heathland Surveys carried out in 1978, 1987 and 1996 by the Institute of Terrestrial Ecology. The focus of the survey was dry heath, wet heath, humid heath and peatland as the dominant heathland vegetation. The surveys were based upon detailed research carried out on the heathlands of Dorset by ecologists such as S. Chapman and N. Webb and, therefore, for the purposes of this thesis, a classification based on such research was deemed more appropriate than a national vegetation classification for heathland. For the purpose of this research heathland, from herein defined as ericoid dwarf shrub vegetation, is made up of several dwarf shrub vegetation types outlined below and as described by Chapman *et al.* (1989):

1. <u>Dry heathland</u>: common heather (*Calluna vulgaris*) dominant with bell heather (*Erica cinerea*), bristlebent grass (*Agrostis curtisii*) and dwarf gorse (*Ulex minor*) or western gorse (*Ulex gallii*).

2. <u>Humid heathland</u>: common heather (*Calluna vulgaris*) dominant but with cross-leaved heath (*Erica tetralix*) or Dorset heath (*Erica ciliaris*) and purple moor-grass (*Molinia caerulea*).

3. <u>Wet heathland</u>: cross-leaved heath (*Erica tetralix*) or Dorset heath (*Erica ciliaris*) dominant with moss species *Sphagnum compactum* and *Sphagnum tenellum* and purple moor-grass (*Molinia caerulea*).

4. <u>Peatland</u>: valley mire with cotton grass (*Eriophorum angustifolium*), species of moss (*Sphagnum*), rush (*Juncus*) and sedge (*Carex*).

2.2.2 Historical development of the Dorset heathlands

The heathlands of Dorset are lowland heathlands, as opposed to upland heathlands or moors. Defining lowland heathland as land under one thousand feet dominated by dwarf ericoid shrubs does not adequately convey the composite nature of the lowland heathland habitat. The principal features of the Dorset heathlands as compared to other British lowland heathlands are, according to Moore (1962), that they border the sea and Dorset is the meeting place for a number of eastern and western elements in the flora and fauna, for example, the overlap of dwarf gorse (*Ulex minor*) and western gorse (*Ulex gallii*). The Dorset heathlands have developed on the sandy, acidic, tertiary deposits (the Bagshot Beds) of the Poole Basin following forest clearances which began in the late Bronze Age, about 3600 B.P. (Webb & Haskins, 1980). The open woodland was cleared and heathland and hazel woodland developed. This transition was aided by the pastoral activities of the inhabitants of the area and a deterioration in the climate. This position was largely unchanged from the Iron Age to the 18th century (Webb & Haskins, 1980).

Isaac Taylors' maps from 1759 and 1765 suggest that at that time there were 39,960 ha of heathlands in the Poole Basin, Dorset. At the time of the first Ordnance Survey maps, (1811 Dorset and 1817 to 1818 Hampshire), about 30,400 ha (80%) of the land of Dorset constituted heathland according to Moore (1962). Traditional uses of heathlands, including rough grazing and fuel gathering, were practised well into the 19th century. These vast heathlands extended uninterrupted from near Dorchester to Southampton's waters. Bournemouth grew from a village of 695 people in 1810 to a town of 16,000 by 1881. By 1896 it had covered much of what was once Poole Heath, yet the total area of heathland was still an almost contiguous area of 23,000 ha (Moore, 1962). Urbanisation continued at an increasing rate from 1896 to 1934. The Forestry Commission began planting large plantations shortly after World War I. The Land Utilization Survey of 1934 showed the area of heathland had been reduced to 18,200 ha. Urbanisation, mineral extraction, forestry plantations and agriculture caused the area to be reduced once again. Moore's own survey in 1960 found only 10,000 ha remained and the heathland had been broken into over one hundred fragments. Between 1750 and 1934 the rate of loss of heathland was in the order of 100-150 ha per annum but between 1934 and 1973 this rate had trebled. Rippey (1973) revealed that of the 6,100 ha of the Dorset heathlands remaining, only 120 fragments extended over 4 ha or more. By 1980 only 14% of the heathlands recorded by Isaac Taylor in 1750 had survived. 160 fragments of heathland extended over 4 ha or more and the remaining 608 sites were less than 4 ha. There were only 14 sites which extended over 100 ha and these represented an area of 49.1% of the total remaining heathland in 1980 (Webb & Haskins, 1980).

Webb (1990) surveyed the changes in the heathlands of Dorset between 1978 and 1987. He found that the area once again decreased but by 5% or 425 ha. The main causes of these losses were conversion to farmland (46%) and urban and industrial development (50%). Further, there was a substantial increase in scrub and woody vegetation. Indeed, this was the most striking change recorded. The invasion of the heathlands by gorse (*Ulex europaeus*), birch (*Betula*) and pine (*Pinus*) caused an increase in scrub vegetation of 15%. The area of carr also increased. Webb also drew attention to the number of areas of humid and wet heathland where there was an invasion of tree seedlings. These declines were offset by expansion of heath in other areas. For example, tree felling accounted for an increase of 370 ha. However, this was a prelude to replanting and was, therefore, only a transient gain. Webb (1990) found the greatest losses were in the area around Poole Harbour. He also found that humid heathlands increased in extent (which he attributed to the fires of 1978) and there was a small decrease in the extent of wet heathland. Despite these changes there seem to have been few qualitative changes in the flora and fauna of the heathlands. Of the heathland vascular plants in Dorset mentioned by Mansel-Pleydell in 1895, five have since become extinct (Moore, 1962).

2.2.3 Summary

For the purposes of this research, the heathlands of Dorset were defined as dwarf shrub vegetation. That is, the heathlands were classified as any combination of dry heath, wet heath, humid heath or peatland vegetation types. The dwarf shrub vegetation of Dorset is semi-natural and is dominated by dwarf ericoid shrubs. It is a resource ultimately in danger of great losses if fragmentation is permitted to continue at its recent rate. Today the dwarf shrub vegetation has been reduced to a mosaic of patches in a matrix of forest, agricultural and urban land.

2.3. Heathland dynamics

A review of the ecological processes in action both in lowland heathlands in general and in the dwarf shrub vegetation of Dorset in particular is presented here. The main ecological (as opposed to anthropogenic) process affecting heathlands is succession. Heathlands are plagio-climax communities. That is, if succession is not controlled the heathlands will revert to woodland. The dwarf shrub vegetation of Dorset is no different and, therefore, it is necessary to control succession to conserve what little of the dwarf shrub vegetation remains. To do this, one must first understand the process of succession, and discover what factors are most likely to affect it in a fragmented environment. Succession in vegetation in general is examined as well as succession in heathlands (succession from heath to non-heath species) with particular reference to the dwarf shrub vegetation of Dorset.

2.3.1 Vegetation succession

Succession is a directional temporal change in species composition or relative abundances and is a central theme in plant community ecology (Miles, 1987; Glen-Lewin *et al.*, 1992 and Miles & Walton, 1993). It has long been recognised but little studied that the rate and pattern of succession may also reflect spatial factors (Glen-Lewin *et al.*, 1992). Indeed among over a thousand studies of plant secondary succession (Rejmánek, 1995) Holt *et al.*, (1995) were unable to find a single experiment specifically designed to asses the rôle of habitat area for succession in isolated patches. However, the present research aimed to build a model of change based on factors which affected both the rate and pattern of the spatial process of succession.

2.3.2 Succession in heathlands

It is only in rare heathland habitats, where continued wind pruning or layering in moist humus prolongs the life-span of individuals, that heathlands have a natural tendency to survive indefinitely. In the more moderate conditions where heather (*Calluna vulgaris*) has become dominant following forest destruction, each individual bush normally passes through a series of growth phases (see below). The rate at which the whole process takes place varies considerably according to habitat and geographical location.

Calluna, left to its own devices, will succumb to the process of succession. The lifecycle of a *Calluna* stand can be loosely described as a series of stages: pioneer, building, mature and degenerate. The pioneer stage is the period of establishment and accounts for the first six to ten years of growth. The building phase is the most vigorous growth phase lasting between seven and fifteen years. Within a period not usually exceeding twenty years the mature stage is reached. Gaps appear in the canopy of a *Calluna* stand and gradually enlarge until, on reaching the degenerate phase at the age of thirty to forty years whole individual bushes die (Mars, 1988; Barclay-Estrup & Gimingham, 1969; Gimingham, 1960; Watt, 1947). The spaces left are seldom filled immediately by a new generation of *Calluna* plants, except in more moist habitats where layering may occur. Instead, this is an opportunity for other species to establish. Sometimes these are other plants of the heathland community such as bracken (*Pteridium aquilinum*), or grasses such as wavy hair-grass (*Deschampsia flexuosa*) or common bent (*Agrostis capilliaris*). However, the gaps may provide a niche for the entry of shrubs such as gorse (*Erica spp.*) or trees such as *Betula*, *Pinus spp.* or oak (*Quercus*). Heathland vegetation is inevitably potentially unstable and liable to change (Gimingham, 1992).

The main species forming plagio-climax dwarf shrub vegetation communities in Dorset (and other lowland heathlands) include cross-leaved heath (*Erica tetralix*), bell heather (*Erica cinerea*), *Calluna vulgaris,* dwarf gorse (*Ulex minor*), western gorse (*Ulex gallii*), Dorset heath (*Erica cilirais*) and mire species such as grasses (*Molinia*) and *Sphagnum spp.* Prentice *et al.* (1987) suggest that both *Erica spp.* are early successional species. Alone *Erica tetralix* and *Erica cinerea* would have short lives, quickly reach maximum extent and begin to die back. Generally, however, *Erica spp.* grow well at first but soon become surrounded by species such as *Calluna* and are vulnerable to competition. *Calluna* bushes grow more slowly than either *E. tetralix* or *E. cinerea*, but grow larger and, therefore, they have the advantage over the *Erica spp.* in the long term. In a grazed community, the *Erica spp.* will, however, grow more quickly than *Calluna.* The *Calluna* species will predominate in the end because its prostrate form allows individuals to grow large and compete for restricted growing space more effectively than individuals from the other two species. The pattern of succession in these three species outlined above, did, according to Prentice *et al.*, (1987), reflect the vegetative successions they observed in the field and sufficiently explained the compositional dynamics of a heathland community.

Succession is not limited to change in heathland species. Rather, heathland species can themselves be invaded leading to succession from heath to scrub. Heathlands rarely allowed to reach their climax (woodland) due to management practices; different heathland sites have different climax vegetation, for example pine woodland or oak woodland. Previously, heathland did not reach their climax vegetation types due to traditional uses of heathlands, such as grazing. Further, it was misleading to imply succession proceeds deterministically (Clements, 1916) as sites may show different trajectories (Miles, 1987). When gaps in the heathland occur and succession is not held in check, what is the result? If *U. europaeus* invades heathland, quite substantial areas of the heathland will remain intact. This seems to be because *U. europaeus* does not form an extensive canopy, therefore, heathland species can survive in a mosaic of *U. europaeus. Pteridium aquilinium* may invade old *U. europaeus* sites, and when it does invade few heathland species tend to survive because its dense canopy creates too much shade (Bullock *pers. comm.*). *Betula* succession into heathland appears to take one of two routes. It either invades directly or replaces *U. europaeus* bushes which have already invaded the heathland. *Pinus spp.* appear to invade directly. Both *Betula* and *Pinus spp.* shade out heathland species and cause dramatic changes in soil structure and fertility preventing the establishment of heath species. It is these successive species whose establishment in heathland needs to be controlled. This cycle of succession occurs when gaps appear in the heaths and there is an available invasive species seed source (Mitchell *et al.*, 1997).

2.3.3 The effects of management on heathland environments

Heathlands can be managed to arrest succession. The most commonly used methods of management, which are based on traditional practices, are grazing and burning (Webb, 1986; Gimingham, 1992). However, Moore (1962) in his survey of Dorset, found that only 607 ha

(6%) of the total lowland heathland were grazed by stock. He noted that small heathlands tended to turn to grass heathlands if over-grazed, or pine woods if left ungrazed. Light grazing, especially by cattle and sheep can be used to suppress scrub such as *Betula.* Cattle, sheep and ponies check the growth of vigorous competitive grasses such as purple moor-grass (*Molinia caerulea*) and, thus, encourage a greater diversity of heathland vegetation (Bullock & Pakeman, 1997). Trampling by cattle can also reduce the spread of *Pteridium aquilinum.* In addition, grazing produces a range of vegetation heights and structures which is beneficial because it increases habitat diversity. Grazing also prolongs the life-cycle of heather (Michael, 1992).

Controlled burning, together with other traditional methods of heathland management (such as grazing, turf-stripping and cutting of scrub and bracken), prevents tree and scrub colonisation, halts degeneration of the scrub layer and maintains soil nutrient concentrations (Webb & Haskins, 1980). Well-controlled fires remove most of the bushes without becoming too hot, so leaving most of the moss and litter layers intact on the soil surface, protecting the stem bases and permitting vegetation regeneration (Gimingham, 1992).

On the whole, grazing and burning breaks the life cycle of heather before the end of the building phase and, therefore, encourages rapid vegetation regeneration, virtually bypassing the pioneer phase and leading to reconstitution of a building-phase canopy within two or three years. Therefore, both are useful tools for arresting succession.

Other management practices involve the re-establishment of heathland species rather than the control of succession. Webb *et al.* (1995) found that the Dorset heathlands cover an area of approximately 5,500 ha and 4,400 ha of grassland had been converted from heathland in the last thirty years. Further, 28% of these grasslands had great potential to be restored to heathland and would provide considerable gains for wildlife conservation.

The traditional methods of heathland management (grazing and burning) during the late 18th century had mostly died out by the time of World War II (Webb & Haskins, 1980). It was not until about 1987 that any extensive organised conservation management was carried out on the Dorset heathlands. Today this management consists largely of bracken spraying, a little controlled burning, grazing and scrub cutting. Succession must be arrested for the heathlands of Dorset to survive. The best method for achieving this depends on the type of lowland heathland one wishes to maintain. Varying management practices have been utilised in Dorset but they have been carried out apparently without collusion between different agencies (English Nature, National Trust, Royal Society for the Protection of Birds, Herpetological Conservation Trust and Dorset Wildlife Trust). One of the specific aims of this research, therefore, is to build a database of heathland management practices in Dorset to see the effect of each kind of management on the survival of the heathlands. The effect of this new kind of conservation management will be examined in detail in this research.

The management of heathland is necessary to maintain the range of heathland habitats required to support its characteristic flora and fauna. These include areas of bare ground and heathland grasses, gorse and scrub, wet heathland, valley mire and open water. Heather must be actively managed to ensure that its full range of growth stages are present and to encourage it to regenerate successfully. In the absence of management, lowland heathlands tend to be invaded by *Pteridium aquilinum*, scrub species such as *Betula, Pinus spp.* and *Rhododendron ponticum* and trees and are eventually replaced by woodland (Michael, 1992).

2.4 Fragmentation

Succession means not only invasion or the spread of non-heath (dwarf shrub) species, but also the loss or decline in dwarf shrub species. Succession is rarely examined spatially, that is, it is rarely considered in terms of the spatial components of the landscape (Holt *et al.*, 1995). By examining fragmentation, the spatial aspect of succession in a dwarf shrub environment can be examined. To do this, it is necessary to examine how the attributes of fragments, that is size, shape, species present, edge effects and context, affect the rate of succession in a dwarf shrub environment, which will in turn affect fragmentation (either causing or preventing further fragmentation).

2.4.1 The effect of fragmentation of heathlands

Dorset's heathland fragments represent a type which Forman and Godron (1986) would describe as 'remnant'. The fragments have most often resulted from, or been isolated by disturbance of the surrounding area. Webb and Vermaat (1990) distinguished three types of heathland fragment. Firstly, large fragments with low diversity of heathland vegetation types and high levels of dominance of a few species. Vegetation on these fragments corresponds with that regarded as typical heathland. Secondly, small fragments which have been created by the invasion of heathland by surrounding vegetation. These show a high diversity of vegetation types and few dominant species (species tend to be equally abundant). Finally, there are small fragments which have a low diversity of vegetation types. Many fragments in this group have been formed recently by isolation (*i.e.*, anthropogenic land use change) and not succession.

As fragment size decreases, diversity increases until a point is reached where the rate of change in species is considered unacceptable (*i.e.*, the species are no longer considered to be typical heathland species) for the purposes of heathland conservation (Webb & Vermaat, 1990). Where fragments of vegetation represent examples of plagio-climax communities, invasion from surrounding vegetation is of prime importance. Hence, the nature of the surroundings and susceptibility to invasion are important characteristics of the patch or fragment (Webb & Hopkins, 1984). In these circumstances, the patch should be viewed as a component of the landscape in which it occurs (Fagan *et al.*, 1999; Lavers & Haines-Young, 1993; Wilcove *et al.*, 1986; Webb & Hopkins, 1984). There are, therefore, several attributes of patches which, according to ecological theory, play an important rôle in patch dynamics with particular reference to heathland patches. Such attributes include fragment size, fragment shape, species density or area, edge effects and context (Baskent & Jordan, 1995; LaGro, 1991; Rex & Malanson, 1990; Moore, 1962). Many of these attributes are related to and are affected by the scale of the fragment (Lord & Norton, 1990). It is these attributes which will be used in this research to investigate the spatial dynamics of the heathlands of Dorset.

Edges not only provide the juxtaposition of two distinct habitat types (both of which may be necessary for the activities of an edge adapted species), they are also subjected to physical conditions not present in the patch interior (Forman & Godron, 1986; Lavers & Haines-Young, 1993). Wilcove *et al.* (1986) suggested that edge effects may penetrate for several hundred metres into fragments. Isolated patches differ from many other habitat islands because they are usually surrounded by communities which are richer in species and are therefore, under continual pressure from colonization and succession (Webb & Hopkins, 1984). When ecological aspects of edges have been examined, research typically emphasised patterns of increased species richness in habitat edges and analyses of vegetation transitions near edges (Fagan *et al.*, 1999). However, in this research the focus is on the mechanisms through which edges alter ecological processes, in particular, succession. According to Fagan *et al.*, (1999) there is a critical need to understand the processes through which habitat edges make an impact on species dispersal and community composition in fragmented homogeneous landscapes. Further research is necessary to examine the rôle of edges in the survival of a dwarf shrub fragment.

Moore (1962) suggested that 'when the habitat of an ecosystem is reduced in size, edge effects become important and the key (characteristic) species become increasingly liable to extinction through inbreeding or accident'. He concluded therefore that the stability of a habitat is to a large extent a function of its size, with the smallest viable size of habitat being the smallest which supports a viable population of its weakest characteristic species. The larger the fragment, the more likely it is to retain a greater complement of the original species and some intact interior (species-area curve). A smaller patch of heath is likely to be invaded much more quickly than a larger patch and thus will be lost much more easily than a larger patch of heath. This process can be illustrated if we examine the rate of succession. If the rate of succession is constant for all fragments irrespective of size, then smaller patches will be invaded more quickly than their larger counterparts in the sense that percentage change in area of heath will be much greater for smaller fragments than for larger ones over a specific time period. Seagle (1986) modelled a dynamic environment using a landscape dynamics model (a first-order Markov model). He included variables such as landscape size, disturbance frequency and competition between colonising species. The results showed that larger landscapes exhibited greater habitat diversity and constancy, and species richness increased with area. Small landscapes supported smaller populations and these were more susceptible to local extinctions. Thus, it can be concluded that area or size of a patch, be it heathland or otherwise, seems to have considerable influence on the survival of a patch.

Patch shape has received relatively little attention in ecological literature. However, the interaction of patch shape and size influence a number of ecological processes (LaGro, 1991). The shape of a patch is likely to influence the survival of a patch. The most likely effect that shape exerts on ecological processes is through its control of the ratio of interior to edge in a patch. The ratio of interior to edge may alter the function of the entire patch. More opportunity arises for exchanges (species dispersal etc.) when more edge exists. Shape alters the perimeter to area ratio: a circle minimises it, more convoluted shapes increase it. Shape also alters the connectivity within a patch, within a circle all points are within a minimum distance and more convoluted shapes produce more isolated areas (Rex & Malanson, 1990). Area-to-perimeter ratios are commonly used to measure shape (Baskent & Jordan, 1995). The greater the perimeter of the patch for a fixed area the more edge effects play a part in the ecological processes at work in the patch. In particular, long thin patches have proportionally much more edge and thus, offer greater opportunity for invasion than more round patches (Diamond, 1975). Equally, the more rounded a patch, the shorter the perimeter for a fixed area, meaning that the rate of loss is reduced. Therefore, the proportion of a patch that is edge habitat is substantially dependent upon patch shape.

The composition of habitat types in a landscape and the spatial arrangement of those habitats are the two essential features that are required to describe any landscape according to Dunning *et al.*, (1992). A given element, such as a patch of dwarf shrub vegetation cannot be considered in isolation: its surroundings exert a significant influence on it. It is as important to manage the surroundings as it is to manage a patch to prevent change (Webb, 1992). Changes on a given patch will be as a result of successional processes within a patch and changes generated by the surroundings of a patch. Therefore, for a given patch its future is as much dependent upon on its location in the landscape as it is on its present composition (Webb *et al.*, 1984). What surrounds each patch of heathland should influence greatly the spatial dynamics of each heathland patch. If a patch is surrounded by scrub it is likely to be under considerable pressure from succession whereas a patch surrounded by grassland is likely to have a smaller influx of seeds from invasive species.

Both the area of dwarf shrub vegetation and the area of invasive species within a patch will influence change within that patch. The initial state of a patch will dictate the rate of succession where the rate of loss is exponential. Therefore, greater areas of invasive species in a patch, or in the edge of a patch make a patch more susceptible to change and the rate of succession increases exponentially with area of invasive species. Further, the density of dwarf shrub vegetation within a patch will influence its survival. The more dense the coverage of dwarf shrub vegetation, the less fragmented it is and the less likely it is to change as succession depends upon the presence of a seed source (Mitchell *et al.*, 1997).

In summary, heaths exist as fragments (or patches) of different sizes. Within fragments there are patches of different vegetation - dry heaths, grasslands, scrub etc. Each fragment is susceptible to succession. Succession may be affected in turn by species density, patch size, spatial configuration (what surrounds a patch), the shape and perimeter of each patch, to name but a few. Change in area of dwarf shrub vegetation will be examined in relation to several factors (patch size, shape, perimeter edge effects etc.) which from the literature, appear to influence the process of succession.

2.5 Ecological modelling

Models are an abstraction or simplification of a process or form, rather than a replication of the process or form. They do not describe the real world exactly and often do not even attempt to do so. Models are built because they help to (1) define the problem to be studied, (2) organise our thoughts, (3) understand our data, (4) communicate and test that understanding and (5) make predictions. A model is, therefore, an intellectual tool (Starfield & Bleloch, 1986). Models based upon ecological knowledge are powerful tools in understanding ecosystem behaviour and for setting up research priorities. The understanding may be qualitative or semi-quantitative, but either has been shown to be important for ecosystem theories and environmental management (Jørgensen, 1995).

2.5.1 Introduction to ecological modelling

Ecosystems can be extremely complex and the difficult part of modelling is, therefore, to select the ecologically relevant components and processes in a given problem context, which requires a profound ecological knowledge. The first step in producing an ecological model is to define the problem and the definition needs to be bound by the constituents of space, time and subsystems. The bounding of the problem in space and time is usually straightforward, and consequently more explicit, than the identification of the subsystems to be incorporated into the model (Jørgensen, 1995).

There are varied approaches to modelling heterogeneous landscapes (DeAngelis *et al.*, 1985; Baker, 1989; Turner & Gardner, 1991) each producing impressive results. Therefore, many kinds of ecological model could have been used to build a predictive model of change. Indeed, several types of model were considered for this analysis including transition models, cellular automata, neural networks and neutral models. However, the focus of this research was to quantify the variables affecting change in area of dwarf shrub vegetation as well as to build a predictive model of change. Models such as those outlined above may be used in a predictive sense but provide limited insight into the causes of change.

Transition models have been used frequently to predict changes in vegetation (Acevedo *et al.*, 1996; Johnston *et al.*, 1996; Pastor *et al.*, 1993; Usher, 1981; Lippe *et al.*, 1985). Such models project an initial distribution among states forward and therefore, simulate changes over time. Transition models are stochastic as opposed to deterministic because model output is based on a probability transition p_{ij} between states *i* and *ij* (Baker, 1989). Transition models are less than suitable for the current application for several reasons. First, the assumption that transition probabilites are stationary over time is questionable. Second, such models are unable to accommodate higher-order effects tending to focus on temporal change rather than spatio-temporal change. Further, such models tend to simulate a point in space and extrapolate its findings for the landscape as a whole therefore, assuming the landscape to be homogeneous (Hunsaker *et al.*, 1993; Sklar & Costanza, 1991; Baker, 1989). However, ecological changes are not so simple and a landscape is rarely homogeneous. Further, the state of a cell is not simply a function of its initial state but is influenced by the cells surrounding it. Therefore, a transition model was not.

Cellular automata have often been used to model landscape change (for example, Jeltsch & Wissel, 1994; Colasanti & Grime, 1993; Silvertown *et al.*, 1992; Iwasa *et al.*, 1991; Inghe, 1989; Green, 1989; Czárán & Bartha, 1989; Czárán, 1989). Cellular automata models describe the dynamical behaviour of a system treating space and time in a discrete fashion (Wolfram, 1984; Silvertown *et al.*, 1992) and are helpful to understand the self-organisation of spatial patterns following distinct rules (Breckling & Müller, 1994). Such models describe the behaviour of a system treating space and time in a discrete fashion (Silvertown, 1992; Wolfram, 1984; Wolfram, 1983). A cellular automaton uses a regular lattice of cells, the states of which vary governed by a set of local rules. Each cell can have a range of possible states. The local rules apply equally to every cell and determine at each iteration what the state of each cell will be as a function of its current state and the state of the neighbouring cells (Silvertown, 1992). Therefore, unlike a transition model a cellular automaton is a spatio-temporal model. However, cellular automata can provide insight into the causes of landscape change only after suitable parameters have been chosen to input into the model. That is, to model successfully a system such as a dynamic landscape, it is necessary to have prior understanding of the causal factors of change in order to devise parameters (or rules) upon which the cellular automata modelling approach is based. This analysis sought to identify and quantify the variables that affect change in the heathlands of Dorset. Therefore, cellular automata were deemed to be an unsuitable model.

Neural networks were also considered as a valid approach to model building. Neural computing is the study of networks of adaptable nodes which, through a process of learning based on examples, stores experiential knowledge and makes it available for use (Aleksander & Morton, 1992). The term 'neural networks' is used to describe a number of different models intended to imitate some functions of the human brain (Davalo & Naïm, 1991). That is, the nodes of the neural net, like the nodes of the brain, are adaptable, they acquire knowledge through changes in the function of the node by being exposed to examples. However, both in a neural network and the brain, very little is known of the details of how this happens (Aleksander & Morton, 1992). Therefore, although a neural network can be used to model change, the actual causes of such change are difficult to interpret. Neural networks were discounted leading to an alternative approach to model building being considered.

Neutral models are generated without hypothesising spatial factors that regulate the distribution of resources or organisms (Caswell, 1976). A neutral model is one used to generate an expected pattern in the absence of specific processes, which is then tested against observation or against predictions of alternative models that explicitly include the processing question (With & King, 1997). Therefore, the neutral model provides a scale of reference or a baseline for evaluating the effect of processes that are not in the model. The resulting patterns from such models are neutral to the physical and biotic processes that may shape real landscapes (Gardner & O'Neill, 1991). As such they provide a basis for statistical testing of observed landscape patterns, or those generated by explicit models and hypotheses of how processes affect landscape pattern (With & King, 1997). Although neutral models permit the development of spatial indicies to describe landscape patterns, it is a misuse of such models to assume that results can be applied directly to real landscapes as they are just part of the larger theory of landscape pattern and process from which hypotheses are generated (With & King, 1997). In short, neutral models may provide some insight into the causes of change, but such insights are limited both in their scope and application.

One final family of models was considered, these were correlation analysis and regression models. This research sought to isolate the factors, which caused change to facilitate the prediction of change. A statistical model, in particular correlation and regression analyses, allow the user to identify the variables affecting change and facilitate the prediction of change. Where the aim of an analysis is to predict (in a statistical sense) one property from the measurements on one or more others, then regression is the proper technique (Webster, 1989). Therefore, correlation analysis was chosen to measure the strength of the relationship between change and several factors, which from ecological theory were likely to influence change. Further, when the causal factors behind such change were isolated, regression was used to predict such change. Although regression is a simple and, therefore, commonly used technique for prediction, the correct use of regression depends upon several assumptions being met. This was an important consideration in the choice of regression for model building in this analysis.

2.6 Regression models in ecology

The intention of modelling is to enhance one's understanding of the available data using a quantitative and repeatable process. Further, the general aim of statistical modelling is to derive a mathematical representation of the relationship between the mean of an observed response variable and a number of explanatory variables and obtain a suitable frequency distribution for random variation (Collett, 1991). The initial choice of explanatory variables is normally determined by the current understanding of the biology of the system to be modelled (Nicholls, 1991). The modelling process identifies important explanatory variables and the final model may be useful in deriving predictions. A 5% level of statistical significance is normally used in the modelling process. Statistical modelling also invokes rules other than statistical significance such as parsimony and biological significance (Neave *et al.* 1996). This section outlines the main features of bivariate regression and multiple regression analysis and their use for ecological model building and prediction. Significance testing and the analysis of residuals will also be examined.

2.6.1 Introduction to regression analysis

The word regression has an odd etymology. In 1886 Francis Galton formulated his 'law of Universal regression' (Galton, 1886), which indicated that each peculiarity in man is shared by his kinsman but on the average in less degree. Galton was describing the height of sons in relation to the height of their fathers. He discovered that the heights of sons of taller than average fathers 'regressed' back towards the average. Today we use the word 'regression' to mean fitting a line to a plot of one variable against another (Williams, 1993).

Regression is essentially about prediction (Webster, 1989). Regression illustrates the relationship(s) between variables. Given knowledge of the variable X and its relationship with the variable Y, regression analysis allows us to use particular values of X to predict the corresponding values of Y. Prediction is an important tool to the ecologist. For example, predicting which species is most vulnerable following habitat fragmentation (as in the case of the heathlands of Dorset) is one of the most pressing problems facing conservation biologists (Sarre *et al.*, 1995). This predictive relationship can be shown in terms of the line of best fit, or in terms of the mathematical definition of this line, called a *regression line.*

2.6.2 Bivariate regression analysis

To understand regression one should consider how a line on a graph can describe the relationship between sets of scores on two variables. Firstly, a line must be found that, when translated into equation form, can describe the relationship between the two variables. The equation for that line is called the *regression equation* (Mason *et al.,* 1991). Although an infinite number of lines could be drawn to summarise the points in the scatterplot, the *least-squares regression line* is unique. The regression line defines the basis for predicting values of *Y*, given values of *X*. The regression equation tells us the best-fitting mathematical linear relation between *X* and *Y* values. That is, given a value of *X*, it tells us what must be done to derive the best estimate of a value of *Y*.

$$Y' = a + bX$$

where *Y'* is the predicted value of *Y* for a selected *X* value.

a is a constant: the value at which the straight line intersects the *Y*-axis.

b is also a constant and is the slope of the straight line.

X is any value of *X* that is selected (Mason *et al.*, 1991)

The slope tells us how many units the variable *Y* increases for every unit increase in *X*. Generally speaking, *a* and *b* are known as *regression coefficients* (Williams, 1993). The statistical aim in fitting a regression line is to place it as close as possible to all of the observations. The adopted definition of 'as close as possible' is that it should minimise the variance in the squared deviations from it on the *Y* axis (Johnston, 1978). The residual is the discrepancy between the model (regression line) and the data. The line of best fit can, thus, be achieved by minimising the sum-of-squares of the residuals (*least squares fit*) (Watt, 1993). However, for any realistic application, the scatterplot of points will not be depicted perfectly by the line of regression. Not all points will lie on the line exactly, which implies that the independent variable cannot account fully for the dependent variable. This occurs for several reasons. For example, ecologists study complex patterns and flows, with complex processes producing these patterns and flows. It is, therefore, unrealistic to expect one independent variable to explain variation in a regression model fully. Even when multiple influences are considered (multiple regression), some proportion of most real-world processes is either attributable to unknown variables or is the result of unpredictable, random occurrences. Despite the above, regression analysis is used commonly in ecological studies (for example, Sarre *et al.,* 1995; Abramsky *et al.,* 1986; Aitkin & Francis, 1986; Philippi, 1993; Trexler & Travis, 1993, Verboom & Apeldoorn, 1990; Verboom *et al.*, 1991; Apeldoorn *et al.*, 1994; Hanski *et al.*, 1995; Andrén, 1996).

Finally, it should be noted that before employing predictive linear regression in any field of research, several assumptions have to be met, or at least be approximately true (Webster, 1989). There are six basic assumptions (Johnston, 1978):

1. Linearity: the trend in the data can be represented by a straight line.
2. Normality: for a given value of *X*, the *Y* observations are normally distributed around the regression line.
3. Means of conditional distributions: for every value of *X*, the mean of $(Y_i - \hat{Y}_i)$ must be zero.
4. Homoscedascity: the conditional distributions should have equal variances.
5. Autocorrelation: each observation on the independent variable is independent of all others.
6. Lack of measurement error: *X* is measured without error.

Linearity implies that the mean value of *Y* is a straight line function of *X*. Regression analysis fits a straight-line trend through a scatter of points (Kleinbaum *et al.*, 1998). Clearly, if the trend cannot be represented by a straight line, linear regression analysis will not portray it accurately. Although simple linear regression cannot be applied to curvi-linear data, it is often possible to transform the trend into a linear form. This is most commonly achieved by expressing one or both variables as a logarithm (Johnston, 1978). It is also assumed the data are normally distributed. For any fixed value of *X*, the conditional distributions of the residuals of *Y* are normally distributed. If these conditional distributions are normal, then it is almost certain that the distributions of *X* and *Y* are also normal (Johnston, 1978). This assumption makes it possible to evaluate the statistical significance of the relationship between *X* and *Y*, as reflected by the fitted line. If the normality assumption is not much violated, the conclusions reached by a regression analysis in which normality is assumed will generally be reliable and accurate (Kleinbaum *et al.*, 1998).

The means of the conditional distributions should be zero for every value of *X*. If they are not then the coefficients of the regression equation may be biased estimates. However, when deviations from this assumption are relatively small they are not considered serious (Johnston, 1978). The variances in the conditional distributions should be equal. Homoscedascity implies that the variance of *Y* is the same for any value of *X*. That is, that *Y* varies the same amount when *X* is a low value as when *X* is a high value (Kleinbaum *et al.*, 1998; Mason *et al.*, 1991). Homo- means 'the same' and *–scedascity* means 'scattered'. If this is not the case then 'heteroscedacity' is said to exist. If the heteorscedacity is considerable, then the regression coefficients may be severely biased. Logarithmic transformation can be used to remove heteroscedacity. It is also assumed that successive observations of *Y* must not be correlated (Mason *et al.*, 1991). Autocorrelation implies that the *Y*-values area statistically independent of one another (Kleinbaum *et al.*, 1998). Most ecological data are spatially autocorrelated as are the data used in this analysis. However, this does not necessarily imply the residuals are autocorrelated and therefore, this assumption is not necessarily violated. Finally, *X* should be measured without error in order to carry out predictive regression (as is the aim of this research). However, if regression is being employed as a technique for calibration then one variable should be measured without error and if regression is being used to measure a functional relationship then it is assumed there is no error in either *X* or *Y* (Webster, 1989).

2.6.3 Multiple regression analysis

The multiple regression model offers a great range of analytical possibilities for the study of the complex real world (be it ecological or otherwise) with the promise of greater understanding of the matrix of direct and indirect links between variables. Multiple regression analyses, like bivariate regression, can be used to test hypotheses and also to generate them (Johnston, 1978).

Multiple regression makes it possible to bring more than one predictor variable to bear in predicting scores on a given variable. The effect of each explanatory variable is analysed separately and models are built by means of multiple (usually linear, often stepwise) regression procedures, (e.g. Richardson & Lum, 1980; Zar, 1984; Owen, 1989; Crawley, 1993; Philippi, 1993). It can also be used as a method of describing the relative contribution of a series of variables in the prediction of a variable (Williams, 1993; Sarre *et al.*, 1995 & Norris *et al.*, 1997).

The multiple regression case extends the equation for ordinary regression to include other independent variables. For *k* independent variables the regression equation is:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + ... b_kX_k$$

where, X_1 and X_2 are the two independent variables

a is the intercept with the *Y*-axis

b_1 is the rate of change in Y for each unit of X_1

b_2 is the rate of change in Y for each unit change in X_2, with X_1 held constant (Mason *et al.*, 1991).

Like bivariate regression, multiple regression is based on assumptions which should be met before this technique is used in any field of research. The most important of these assumptions are that the independent variables and the dependent variable have a linear relationship. The dependent variable is continuous and at least of interval scale. The variation around the regression line is the same for all values of X. This means that Y varies the same amount when X is a small value as when it is a large value (homoscedasticity). Successive observations of the dependent variable are uncorrelated and the independent variables should not be correlated (Johnston, 1978).

However, multiple regression appears to work well even when one of these assumptions is violated (Mason *et al.,* 1991). Although multiple regression techniques have been applied with considerable success in many ecological and ecological-biogeographical studies, these techniques also have some pitfalls (see Vincent & Haworth, 1983; James & McCulloch, 1990; Philippi, 1993). The most frequent limitation arises from the (multi)collinearity of explanatory variables (Heikkinen, 1996). The independent variables should not be highly correlated. When the independent variables are correlated, this is called multicollinearity. One solution to the problem of collinearity is to combine explanatory variables into a smaller set of linear combinations or principal components that are, by definition, linearly independent of each other (e.g., Osborne & Tigar, 1992; Buckland & Elston, 1993; Eriksson *et al.*, 1995; Heikkinen, 1996). The data should be examined for outliers and influential points that exert undue influence on the parameter estimation and overall fit of the model (Neave *et al.,* 1996).

2.6.4 Correlation

Simple regression analysis models the linear relation between variables; correlation analysis illustrates the degree to which variables are linearly related. Correlation is therefore, a useful aid in interpreting regression analysis. The *coefficient of correlation* is a measure of the strength of the association between the dependent and independent variables. There are three different correlation coefficients commonly used in statistics: Kendall, Pearson and Spearman. The most commonly used is Pearson's product-moment correlation coefficient. It is a valid measure of correlation if the relationship is linear. To remove the possibility of dependence on the scaling of variables, the correlation coefficient is defined in terms of standardised versions of the variables, found by subtracting the mean and dividing by the standard deviation of each variable separately:

$$r = \frac{\sum xy}{\sqrt{\sum x^2 \sum y^2}}$$

where, $x = X_i - \overline{X}$ and $y = Y_i - \overline{Y}$

A measure of correlation that can be more easily interpreted is the *coefficient of determination* (Mason *et al.*, 1991). It is found by squaring the correlation coefficient r (Wonnacott & Wonnacott, 1972). The coefficient of determination is the proportion of the total variation in one variable explained by the other variable. The result is a proportion, that makes it relatively easy to arrive at a precise interpretation. The coefficient of determination is used to provide more insight into the relationship resulting from simple and multiple regression analysis by indicating the proportion of the variation in the dependent variable Y, which is explained by the independent variable(s) X. The coefficient of determination is commonly used in regression analyses for this purpose (for example, Kelly & King, 1995).

$$r^2 = \frac{\sum(\hat{Y}_i - \overline{Y})^2}{\sum(Y_i - \overline{Y})^2} = \frac{\text{explained variation of } Y}{\text{total variation of } Y}$$

It is clear, therefore, that regression is a useful tool of the ecologist for producing not only models but also for prediction. One of the main drawbacks of the regression technique, however, is finding suitable and significant explanatory variables, be they for a patch of heathland or otherwise.

2.6.5 Transforming data

For a regression line to present a faithful reflection of the trend in a dataset it is necessary to ensure that the relationship between two variables is linear. If this is not the case in the 'raw' data, transformations may achieve it (Johnston, 1978). Further, transformations may be used to ensure a variable meets the assumptions of the analysis (see section 2.4.3.2) (Sokal & Rohlf, 1998). A transformation consists of a replacement of measured values by other values (Jongman *et al.*, 1996). Transformation can ensure a better fit of the values in a regression model. Many different mathematical functions may be used to transform data. However, a particular family of simple transformations has proved useful in a wide range of situations. These are the family of power transformations. A power transformation simply changes a data value x by raising it to some power p, giving it a transformed value of x^p. The most commonly used power functions are:

1. $p = 1$ (not transformed)
2. $p = \frac{1}{2}$ (square root)
3. $p = -1$ (reciprocal)
4. $p = \frac{1}{3}$ (cube root)
5. $p = 2$ (square)

Decreasing the value of p reduces the visual effect of the outliers and spreads out lower values. The lower the value of p the stronger the effect of pulling in the upper tail and decreasing it in the lower tail. Increasing values of p have the opposite effect, increasing the spread of the data in the upper tail and decreasing the spread in the lower tail. Separate transformations of each of the variables may be performed to make the distribution of values for that variable more symmetric. Although this is not guaranteed to linearise a relationship, it often does so in practice (Griffiths *et al.*, 1998).

2.7 Geographical Information Systems and object-based modelling

Spatial analyses can be used to investigate spatial relationships within a single spatial data set. This offers particular potential for application in landscape ecology and for the study of species-environmental interactions at regional scales. Ecological research is relatively rich in theory and concepts that relate to processes and ecological functioning, but it is relatively poor in spatial concepts and spatial theory, which underpin the development of spatial analytical tools to enhance the functionality and relevance of Geographical Information Systems (GIS) for use in ecological research.

2.7.1 Introduction to GIS

A GIS is a system of hardware, software, data, people, organisations, and institutional arrangements for collecting, storing, analysing and disseminating information about areas of the Earth particularly in this case for understanding environmental processes (Nyerges, 1993). The hardware and software are used for entering, storing, retrieving, transforming, measuring, combining, subsetting and displaying spatial data that have been registered to a common co-ordinate system. To perform these functions, the data entered into a GIS must include information about the spatially explicit location of an entity, as well as its attributes (Johnston, 1998). The main difference between GIS and computer-assisted cartography is that a GIS can create new information (Parker, 1988).

2.7.2 Data storage and analysis

Spatial attributes record data about the location, topology and geometry of spatial objects. These are characteristics that separate GIS from other kinds of database management systems. This spatial location of objects is recorded either in latitude and longitude co-ordinates, in co-ordinates of one of the standard cartographic projections, or in arbitrary rectilinear co-ordinates with a local origin. One of the useful functions of GIS is the ability to transform spatial data from one co-ordinate system to another, so that maps in different projections can be compared (Bonham-Carter, 1994).

Some GIS use raster data structures while others use vector data structures although all GIS store data about the location and attributes of real-world entities. Rasters and vectors form the two basic data models used in GIS, and they differ in the way they store data. A raster-based GIS, also known as a grid- or pixel-based system, portrays features as a matrix of grid cells, each with an individual data value. A vector-based GIS portrays features as nodes, arcs and polygons (Johnston, 1998). We are predominately interested in the raster data structure as it this structure which has been used for this research. The raster data structure was an appropriate choice as the survey data itself were made of 200 m x 200 m cells forming a raster grid even before it was entered into the GIS. A raster database portrays features as a matrix of equal-area cells that are usually square. The smallest non-divisible element in a raster database is a grid cell. Grid cells are inherently two-dimensional even though the features they represent may be zero- or one-dimensional. Therefore, features that are dimensionless (points) or smaller than the minimum raster dimensions (streams) are difficult to depict in a raster GIS. The appropriate raster size should be comparable to the scale at which the ecological process of interest is operating (Burrough, 1989; Maguire *et al.*, 1991 and Johnston, 1998).

2.7.3 GIS and the spatial dynamics of vegetation

One of the most powerful aspects of GIS is the ability to examine spatially referenced objects over time. Temporal changes in landscape patterns have been analysed with particular emphasis on the effects of anthropogenic and natural processes (Stringer *et al.*, 1988; Turner & Ruscher, 1988 and Turner, 1990). Landscape patterns are characterised by the number of landscape types and the amount of edge between them, by patch shape and indices of dominance, diversity and contagion. Functions, such as proximity functions, have been used to determine contiguity of landscape patches to provide a descriptor for landscape structure (O Neill *et al.*, 1988), or to predict susceptibility and/or the results of disturbance (Gardner *et al.*, 1987 and Cuddy *et al.,* 1996). However, many important ecological questions involve the analysis and prediction of such changes in landscape pattern over time. It is, therefore, necessary to examine how temporal change can be quantified using a GIS. Change detection involves comparing spatially explicit databases from two different time periods to determine the location and nature of changes over time. Change detection with a GIS can reveal the location and spatial extent of change (Wood & Foody, 1993; Michalak, 1993 and Xu & Young, 1990).

Ecologists traditionally detect change by comparing statistical data collected at different times and determining whether the magnitude of change is sufficient to meet a test of significance. Statistical techniques are usually necessary because measurement of an entire population is not always possible, requiring a sample of the population to be selected. GIS change detection differs from this approach in that a GIS database represents the entire population, rather than a sample thereof. Thus, the concept of statistically significant change is generally not applicable in GIS change detection, because populations are being compared in their entirety: any change detected between datasets is significant, regardless of its magnitude (Johnston, 1998). Further, the different types of change can themselves be classified and displayed using a GIS (for example, Jensen *et al.*, 1993).

In the present research, GIS provides a useful tool with which to manipulate the various data into the required format prior to applying regression. Further, it facilitates the production of maps of change capable of illustrating the spatial structure of change.

2.8 Remote sensing

The Dorset Heathland Surveys provided data concerning the area of dwarf shrub vegetation and associated species in Dorset. However, the Surveys provided no contextual data. That is, there were no data concerning what surrounded the areas of dwarf shrub vegetation surveyed. Remote sensing can provide such information. Remote sensing involves the recording of energy in the microwave, infrared and visible regions, as well as the long-wavelength portion of the ultra-violet (UV) region from the electromagnetic spectrum. Wavelength regions with high transmission are called atmospheric windows and are used to acquire remote sensing images. Imaging sensors operating in the solar spectral region (0.4-2.5μm) collect reflected solar radiation. The nature and geographical distribution of Earth surface materials can be inferred from the distribution of reflected energy in this spectral region (Lillesand & Kiefer, 1994).

2.8.1 Introduction to remote sensing

Remote sensors record electromagnetic radiation (EMR) which travels from the source directly through the atmosphere or indirectly by reflection or re-radiation to the sensor. Electromagnetic energy refers to all energy that moves with the velocity of light in a harmonic wave (waves that occur at equal intervals in time) pattern (Floyd & Sabins, 1987). All objects whose temperature is greater than absolute zero emit radiation, but the distribution of the amount of radiation at each wavelength across the spectrum is not uniform (Mather, 1989). Electromagnetic energy can only be detected when it interacts with matter.

The regions used for remote sensing, are sub-divided into wavebands, such as the blue, green, and red wavebands of the visible region. Atmospheric gases absorb electromagnetic energy at specific wavelength intervals called absorption bands. Wavelengths shorter than 0.3 μm are completely absorbed by the ozone (O_3) layer. Particles of liquid water (which constitute cloud) absorb and scatter electromagnetic radiation at wavelengths less than about 0.3 μm. Only radiation of microwave and longer wavelengths is capable of penetrating clouds without being scattered, reflected, or absorbed (Lillesand & Kiefer, 1994; Floyd & Sabins, 1987). The absorption, reflection and transmission of a vegetation canopy is primarily controlled by the physiology and pigment chemistry of its leaves. Multispectral reflectance is related to the area and density of leaves seen by the sensor (Curran, 1985).

2.8.2 Landsat

Landsat satellites -1, -2, and -3 were launched by the US in 1972, 1975 and 1978, and each was decommissioned approximately five years after launch. These early satellites carried Multispectral Scanner System (MSS) sensors which detected radiation in four spectral bands (green, red and two bands of near-infrared (NIR)). Subsequent satellites carried Thematic Mapper (TM) scanners in addition to the MSS scanners. Landsat TM has seven spectral bands, three in the visible part of the spectrum (red, blue and green), two mid-infrared bands and a single thermal-infrared (TIR) band. The additional bands made TM imagery more useful for vegetation discrimination than MSS. TM imagery also has a much finer spatial resolution than MSS which can make it more useful for ecological applications (Johnston, 1998). Therefore, TM imagery has been used for mapping a variety of ecological features (for example, Fuller *et al.*, 1994; Veitch *et al.*, 1995), and will be used in the present research.

2.8.3. Land cover classification and classification accuracy

A common use of remotely sensed imagery has been the production of land cover and vegetation maps. However, before an image can be classified for use in land cover mapping, the image must be corrected. The intent of image restoration and correction is to correct an image for distortions or degradations which occur during acquisition (image correction is discussed in detail in Appendix 1). Further, the precision of the classification achieved depends upon the spatial and spectral resolution of the sensor (Stoms & Estes, 1993). The overall objective of image classification is to automatically categorize all pixels in an image into land cover classes. During classification the spectral patterns in the image are evaluated. That is, different feature types manifest different combinations of digital numbers based on their inherent spectral reflectance and emittance properties (Lillesand & Kiefer, 1994). A supervised classification was carried out for this analysis. The classification was 'supervised' by specifying numerical descriptors of the various land cover types present in the scene. To do this, representative sample sites of known cover type (training areas) were used to compile a key describing the spectral attributes for each feature of interest. Less ambiguous identification of land cover and land use generally requires a ground survey of some description (Wyatt *et al.,* 1993). Rather than carry out another ground survey, the Dorset Heathland Survey data were used as training data for the purposes of classification. A classification is not complete until its accuracy is assessed (Lillesand & Kiefer, 1994). The overall accuracy is computed by dividing the total number of correctly classified pixels by the total number of reference pixels. An error matrix is an effective way of representing classification accuracy as the accuracy of each category is plainly described (Lillesand & Kiefer, 1994; Congalton, 1991). Once an image has been classified and the classification accuracy assessed, it can be used in subsequent analysis.

2.8.4 The integration of remote sensing and GIS

Remote sensing is an important source of GIS data as it provides information on ecological properties that have not been mapped (Ehlers *et al.*, 1991). Both remote sensing and GIS involve the manipulation of spatial data in digital form. Remote sensing allows the measurement and examination of variation of electromagnetic radiation. GIS, in principle, enables the organisation and analysis of these measurements and attribute data to improve the mathematical and statistical modelling of the pattern and processes on the surface of the Earth (Ehlers *et al.*, 1991). GIS, coupled with data from satellite imagery, is proving to be a powerful tool for the development of both general and specialised classification systems (Clarke *et al.,* 1986).

The major disadvantage of satellite imagery as a source of GIS data is its relatively coarse spatial resolution. Satellite images can provide data about plant communities and environmental conditions, but are unsuitable for studies at the individual organism level. Clouds and atmospheric effects also interfere with the quality of the data. Furthermore, because satellite imagery depends on spectral reflectance it is only applicable to those features which have a distinct spectral signal. Despite these drawbacks the integration of GIS and remotely sensed data to facilitate environmental analysis has a distinguished history (Young, 1986; Xu & Young, 1990; Walsh *et al.*, 1990; Davis *et al.*, 1991; Wood & Foody, 1993; Roseberry *et al.*, 1994; Michalak, 1993; Veitch *et al.*, 1995 and Foresman & Millette, 1997).

The integration of data from field observations and remote sensing within GIS offers the potential for rapid, cost-effective surveying and assessment of biotopes of high conservation value (Veitch *et al.*, 1995). However, the usefulness of classifications derived from satellite remotely sensed data as an input into a GIS may be questioned when dealing with environments which display a gradual change (Wood & Foody, 1993). With regards to the heathland of Dorset, the use of remotely sensed data may enable heathland areas to be placed into the context of the surrounding land use. Such a synoptic view may be invaluable when formulating management strategies that consider the landscape as a whole and not just the biotope of interest (Veitch *et al.*, 1995).

2.9 Conclusion

The ultimate aim of this research was to build a predictive, statistical model of dwarf shrub vegetation dynamics in Dorset to aid the conservation of this environment. From an examination of the literature, it is possible to identify the processes at work in such a patchy heathland environment. Succession is the process of most interest since it is predictable. However, the factors which arrest or affect the rate of loss of heathland due to succession are not clear. A number of factors, in particular patch geometry, but also species density, management practices and patch status, are thought to affect rates of change. The model building process will test such hypotheses. The tools used in the modelling process include GIS and both simple and multiple regression. GIS offers facilities for the description and management of spatial environment and ecological data and, with appropriate tools, has the potential to be used to analyse and synthesise interactions and variability at different levels of spatial and ecological organisation (Aspinall, 1984). Regression analysis is a simple modelling technique commonly used in ecology with the added benefit of allowing prediction.

CHAPTER 3

FIELD SITE AND DATA

3.1 Introduction

> 'Twilight combined with the scenery of Egdon Heath evolve a thing majestic without severity, impressive without showiness, emphatic in its admonitions, grand in its simplicity........' (Hardy, 1878)

Two factors were critical to the development of the heathlands of Dorset, southern England. Firstly, the geology of the area, and secondly, the activities of early humans. Therefore, it is necessary to study the geological and anthropogenic influences and their locations in detail to understand the development of this unique and varied habitat. In Chapter 2, the natural history of the heathlands was described in detail. Therefore, this Chapter briefly describes the geology of the region. Further, the datasets used for this research are described in detail. The GIS analysis of the data is discussed as is the development of a database of heathland management for all Dorset. Finally, the response variable and explanatory variables are defined.

3.1.1 The study site

The county of Dorset borders the sea and is situated in southern England (Figure 3.1). The point at which the Hampshire Basin crosses into eastern Dorset is known as the Poole Basin (DWT, 1997). The wealth of flora and fauna has arisen for several reasons. Most fundamentally, the geology and geomorphology of the county are extraordinarily diverse within a relatively small area (Dorset is only 2, 652 km^2) and the derived soils have allowed rich and varied habitats to develop. The county's situation along the English Channel seaboard means that, apart from being in the warmer south of the country, it is subject both to the continental climatic influences of mainland Europe and the maritime influences of the Atlantic. As one moves across the county from west to east, there are rapid changes in geology, a decrease in rainfall and changes in habitat from those based on clay soils, through chalk to sands and gravels (DERC, 1997).

As in other parts of the world, the heathlands of Europe (like those of Dorset) generally belong to acid substrata of low nutrient status. These include stabilised siliceous sand, various types of podzolic soils derived from freely drained parent materials including fluvio-glacial sands and gravels, glacial tills and weathered rock debris, oligotrophic brown earth soils, humic gleys, ranker soils and peat. With some exceptions, heathlands are absent from soils

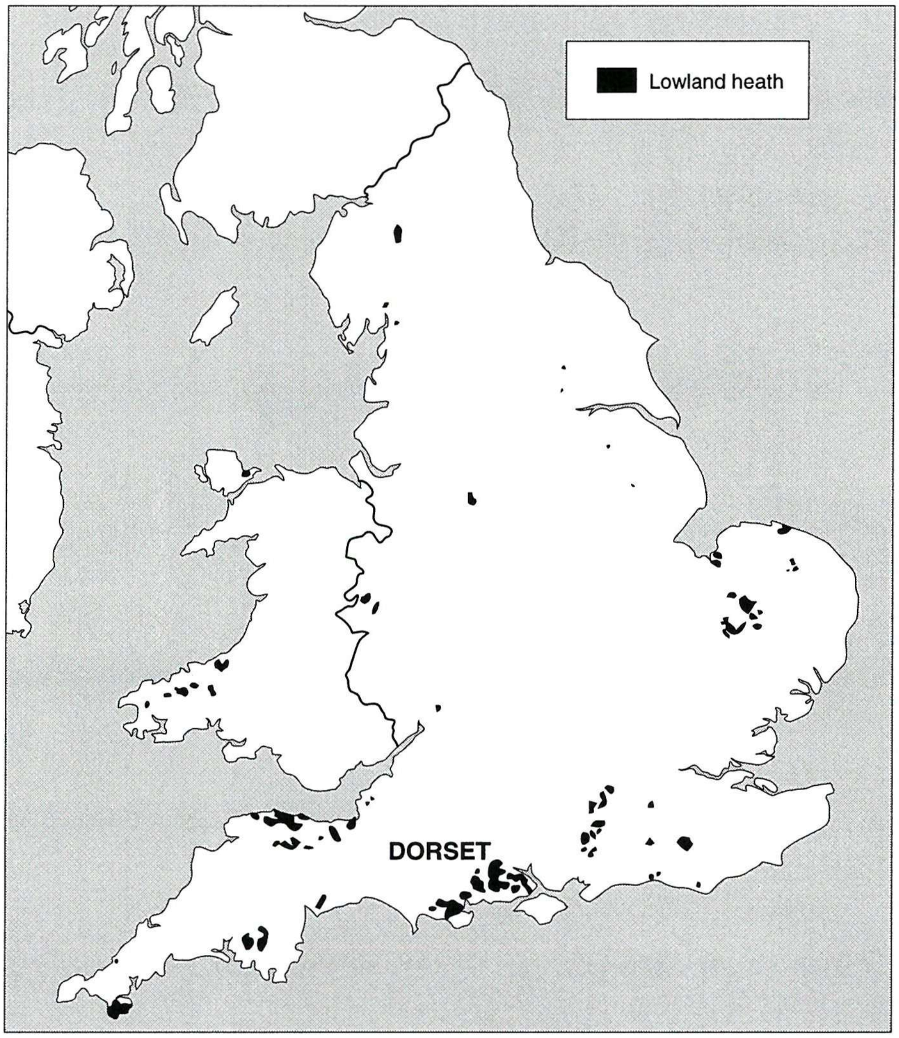


Fig. 3.1 The remaining areas of lowland heatland in England and Wales

rich in exchangeable nutrients, especially calcium. Phosphorus is also deficient. In the majority of heathland soil pH lies in the range 3.4 to 6.5 and the calcium nitrogen (C:N) ratio is high (Gimingham *et al.*, 1979). In Dorset, heathland occurs on the Bagshot beds (Tertiary deposits) in the east of the region in the area surrounding Poole Harbour (the Poole Basin) (Chapman *et al.*, 1989). The Dorset heathlands are typical of lowland heath which occurs at altitudes below 300 m (Webb, 1986). Heathland species are supported by peat, valley gravels, plateau gravels, Bracklesham beds, Bagshot beds, Bagshot sands and Reading beds. These beds have supported heathland since at least Norman times (Moore, 1962).

Virtually the whole of Dorset lies within a shallow trough, which is the Hampshire Basin. The rocks were mainly formed in two separate periods, the older Cretaceous and the Tertiary periods. Bagshot beds and Bracklesham beds (the younger Tertiary deposits) are the most common in the area. These are found within the Wareham main block, Purbeck, Ringwood, Hefthelton, Whitesheet, Uddens and part of Moreton plantations. The beds are a mixture of sands, gravels, and clays which give rise to poorer soils (podzols or peat) (DERC, 1985). The Tertiary Bagshot and Bracklesham beds of the Poole Basin comprise a variety of inhospitable sands and gravels interspersed with clay, and it is upon these that the heathlands of Dorset were formed (DWT, 1997). The heathlands of Dorset, which developed on these Tertiary deposits, form a convenient unit, the eastern boundary of which is formed by the River Avon. This river, together with the River Stour, drains the eastern part of the area into Christchurch Harbour, while the Rivers Frome and Piddle drain from the west of the area into Poole Harbour (Webb & Haskins, 1978).

The county of Dorset is a classic geological area in Britain. The Dorset coast contains good examples of nearly all the formations from the early Jurassic to the Tertiary (Figs. 3.2 & 3.3). These deposits are overlain with alluvial deposits and represent much of the last 200 million years of geological history. Inland, the geology is not as well documented as it is less exposed. The oldest rocks in Dorset date from the Triassic period (approximately 220 million years ago) (DERC, 1985). These rocks are mainly soft muddy rocks, like those, which form the taller cliffs near Lyme Regis. The rocks of the Jurassic period (213 to 144 million years ago) are characterised by clays and shales, which are soft and easily eroded, supported by layers of more resistant limestone, oolite and sandstone. The Cretaceous (144 to 65 million years ago) rocks start with the Purbeck limestones, which are overlaid with the soft and easily eroded Wealden beds. The Cretaceous sequence is mostly represented by chalk. This is the thickest bed of the region and forms distinctive high white cliffs and features such as the Old Harry rocks. The youngest rocks are those of the Tertiary (65 to 2 million years ago). These occur to the east and are composed of sands, gravels and clays. The clays form the basis of Pooles' pottery industry. The sands form Bournemouth's beaches and the dune systems of both Studland and Shell Bay (DWT, 1997).

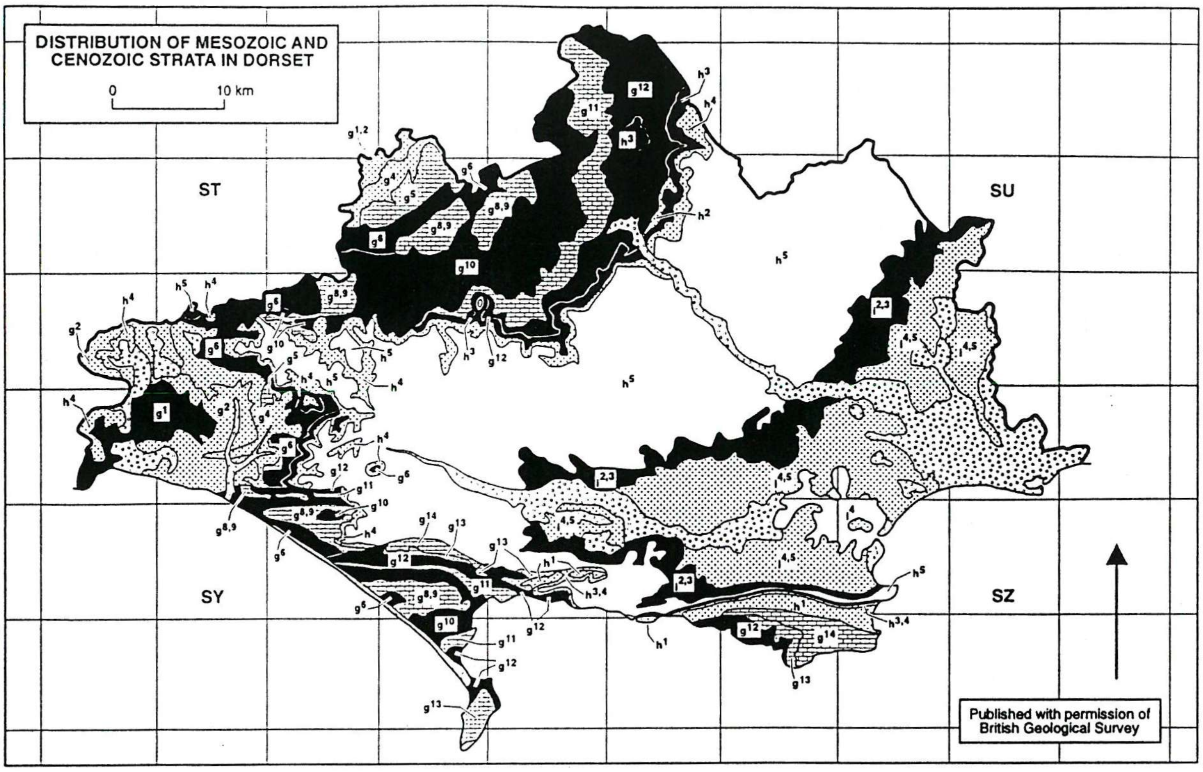


Fig. 3.2 The geology of Dorset.

ERA	PERIOD	EPOCH	Age * Ma		FORMATIONS
CENOZOIC	RECENT	HOLOCENE PLEISTOCENE			Alluvium, Plateau Gravels, Valley Gravels & Head
			25		
			40		(Highest beds missing in Dorset)
	TERTIARY	EOCENE		i 4,5	Bracklesham Beds Bagshot Beds
				i 2,3	London Clay Reading Beds
			55		
MESOZOIC	CRETACEOUS		65		(Top of Chalk missing in Dorset)
		UPPER		h5	Upper, Middle & Lower Chalk
				h4	Upper Greensand
		LOWER		h3	Gault
				h2	Lower Greensand
				h1	Wealden
			140	g14	Purbeck Beds
	JURASSIC	UPPER		g13	Portland Beds
				g12	Kimmeridge Clay
				g11	Corallian
				g10	Oxford Clay
		MIDDLE		g8,9	Cornbrash Forest Marble
				g6	Fuller's Earth
				g5	Inferior Oolite
		LOWER – U. Lias		g4	Down Cliff Clay, Bridport Sands
		LOWER – M. Lias		g2	Eype Clay, Down Cliff & Thorncombe Sands
		LOWER – L. Lias		g1	Belemnite Marls, Green Ammonite Beds, Blue Lias, Shales with "Beef", Black Marl
			213		

Fig.3.3 Key to the geological map of Dorset (Fig. 3.2). *Millions of years ago

As with all lowland heathlands, it was the combination of geology, soils and anthropogenic activity which permitted heathland development. However, the heathlands of Dorset differ from many similar lowland heathlands for several reasons. The immense variety and range of habitats (for example, Dorset is the meeting place for several eastern and western elements in the flora and fauna, hence the overlap of dwarf gorse, *Ulex minor* and western gorse, *Ulex gallii*) is in part the result of the great variety of geological formations in Dorset and is unique in Britain (Moore, 1962).

3.2 The ITE Datasets

This research is based on three datasets, the product of the Dorset Heathland Surveys of 1978, 1987 and 1996. It is an immense dataset with potential to provide key information on the dynamics of the lowland heathlands of Dorset.

3.2.1 The Dorset Heathland Surveys

The first Dorset Heathland Survey was initiated by ITE in 1978 (Webb & Haskins, 1980) and was designed as a large-scale, repeatable survey which provided a baseline for monitoring change (Rose *et al.*, 1999). The Survey was repeated in 1987 and 1996. There are few studies in the literature in which long-term vegetation changes have been made at a landscape scale and the Dorset Heathland Surveys provides one of the best documented examples of the patterns of change in a fragmented biotope over an entire landscape (Rose *et al.*, 1999).

The aims of the initial Dorset Heathland Survey in 1978, were two-fold: first, to provide a revision of previous surveys (Moore, 1962; Rippey, 1973) and, second, to provide a more detailed basis for the assessment of future trends. In particular, a precise definition of the vegetation types recorded and the delimitation of these on the ground was required. To achieve the above, the survey was based on a 200 m grid derived from the National Grid. Each one kilometre cell of the National Grid was divided into twenty five 200 m x 200 m recording cells. This size was chosen as it was deemed the best compromise between that which was readily identifiable in the field and yet was small enough to detect any changes in vegetation. The recording scheme was a modified version of that used by Chapman (1975) for his study of the distribution of *E. ciliaris* on the Isle of Purbeck (Webb & Haskins, 1980).

3.2.2 The 1978, 1987 and 1996 datasets

To carry out the 1978 Dorset Heathland Survey, a field survey sheet was drawn up containing a list of 260 attributes, each of which would be examined for presence or absence, as well as degree of coverage for every heathland survey cell. However, only 184 of these attributes were utilised in the survey. Vegetation characteristics accounted for 109 of the attributes recorded, species records for nine, topographic features for nineteen and land use and management for forty seven. Each attribute was recorded as either absent (zero), present but not abundant (one), well represented (two), or the dominant vegetation type (three). The 1978 field survey was carried out between February and June 1978 (Webb & Haskins, 1980).

The survey was repeated in 1987. With the exception of minor revisions of procedure to meet improved standards of computing, the survey was identical to that of 1978. The field survey was carried out between November 1986 and July 1987. Every site in Dorset which contained heathland was surveyed. In 1978 3,110 cells were surveyed, and this figure rose to 3,360 in 1987. All cells surveyed in 1978 were re-surveyed in 1987 irrespective of whether they contained heathland or not. However, several new areas of heathland developed in the nine year period between 1978 and 1987, and these were also surveyed (Webb, 1990).

In 1996 a new survey was conducted using much the same survey technique but with a number of refinements. In addition, areas (mostly former heathland) with the potential for heathland recreation were surveyed to provide a baseline for restoration or re-creation exercises implemented to meet national and regional biodiversity targets (Anon, 1995). Once again all the cells surveyed in 1978 and 1987 were re-surveyed as well as any new cells of heathland which had developed (Rose *et al.*, 1999). The survey was carried out between March and November 1996. In total 3,993 cells of heathland were surveyed in 1996.

3.2.3 Primary, aggregated primary and secondary categories

The 184 attributes surveyed were divided into 'primary',' aggregated primary' and 'secondary' categories. The primary categories allowed the examination of the spatial dynamics of heathlands vegetation types, for example, dry heath, wet heath, humid heath and peatland. The aggregated primary categories were devised by combining primary categories. For example, dry, wet, humid heath and peatland were combined to form a 'total heathland' category thereby, permitting examination of the dynamics of both dwarf shrub vegetation (heathland) and invasive species as a whole. The secondary categories allowed the examination of the spatial dynamics of invasive species types. Therefore, analysis of the spatial dynamics of dwarf shrub vegetation in Dorset was carried out at the following levels of generalization. Firstly, the vegetation class scale (aggregated primary categories composed of dwarf shrub vegetation, invasive species or 'other'). Secondly, the vegetation type scale (primary categorise composed of dry, wet, humid heath, peatland, scrub, carr and wood etc.), and finally, the individual species scale (secondary categorised composed of invasive species such as *Pinus spp.* and *Betula* etc.).

Primary vegetation categories were defined for the initial 1978 survey and remained unchanged for the following surveys. As outlined above, the primary categories included dry heath, humid heath, wet heath and peatland. These four primary categories define the classification of 'heath' for this study. Dry heath is an assemblage of plants dominated by *Calluna vulgaris*, growing in association with *E. cinerea*, *U. minor* or *U. gallii* and *Agrostis curtisii.* A few other species may also occur, such as *Pteridium aquilinum*, tormentil (*Potentialla erecta*) and heath milkwort (*Polygala serpyllifolia*) (Chapman *et al.*, 1989).

Humid heath is an assemblage where *Calluna* remains the dominant species and grows in association with *E. tetralix*; a mixture containing equal proportions of the two species is often found. Sometimes, *E. ciliaris* is present. Associated species include *U. minor* or *U. gallii* and *Molinia caerulea*. Humid heath tends to occur in poorly drained areas, but may also occur in areas of transition between dry and wet heath (Chapman *et al.*, 1989).

Calluna ceases to dominate in wet heath and may even be absent. Wet heath is characterised by *E. tetralix* with mosses such as *Sphagnum compactum* and *Sphagnum tenellum.* Depending on how wet the soil is species such as *Molinia caerulea*, *Potentilla erecta*, cotton grass (*Eriophorum angustfolium*), deergrass (*Trichophorum cespitosum*), black bog rush (*Schoenus nigricans*), species of sundew (*Drosera*), rush (*Juncus*) and sedges (*Carex*), and the rare marsh gentian (*Gentiana pneumonanthe*) and marsh club moss (*Lycopodiella inundata*) may also be present. The drainage is severely impeded and the water table is within 10 cm of the surface for part of the year (Chapman *et al.*, 1989).

Peatland (strictly valley mire) contains a wider range of species depending on the local conditions. Characteristic plants include *Sphagnum*, *Juncus*, *Carex*, *Schoenus nigricans*, *Eriophorum angustifolium* and common reed (*Phragmites australis*).

The definitions of each primary category, as outlined above, were deemed rather narrow for the purposes of the Dorset Heathland Surveys. Therefore, for the initial survey a number of associated vegetation types were also recorded. These included *Betula*, *U. europaeus* and *Pinus spp.* (Chapman *et al.*, 1989). As part of the Dorset Heathland Surveys, nineteen primary categories were identified for surveying (Table 3.1). The primary categories were defined as

Table 3.1 The nineteen primary categories identified for analysis

Primary Categories			
Dry heath	Wet heath	Humid heath	Peatland
Brackish Marsh	Sand dunes	Bare ground	Open water
Agriculture	Horticulture	Carr	Scrub
Woodland	Grassland	Houses & gardens	Farm Buildings
Industrial buildings	Other buildings	Hedges & boundaries	

vegetation types easily identifiable in the field. For example, wet heath is easily identifiable in the field and was characterised as a combination of secondary categories including *Sphagnum* and/or *E. tetralix*, *Sphagnum spp.* and/or *E. tetralix* and/or *E. ciliaris*, *Molinia*, scattered young *Pinus* and finally, scattered mature *Pinus spp.*

The primary categories were further divided into secondary categories for the surveys. The secondary categories were individual species (for example, *Betula*, *Pinus spp.* and *Quercus*). Few secondary categories were included in this research. Indeed those chosen from the remaining attributes surveyed were invasive species. The remaining attributes included in the survey sheet were used to record species which were either rare or had unusual distributions (for example, dwarf gorse (*U. minor*), western gorse (*U. gallii*) and the marsh gentian (*Gentiana pneumonanthe*)), topographic features such as altitude, aspect and slope and a variety of land uses (Chapman *et al.*, 1989). The secondary categories chosen for analysis are outlined in Table 3.2.

Table 3.2 Secondary categories

Secondary Categories		
Bracken (*Pteridium aquilinum*)	Birch (*Betula*)	Pine (*Pinus*)
Gorse (*Ulex europaeus*)	Rhododendron	Alder (*Alnus*)
Willow (*Salix*)	Oak (*Quercus*)	Mixed deciduous trees
Western gorse (*Ulex gallii*)	Conifers	Broom (*Sarothamnus*)

As mentioned previously (see Section 3.2.2), each attribute was surveyed using a score of between zero and three. The scores were used as estimates of percentage cover for each vegetation type or attribute in a cell. For each grid square attributes were scored on a frequency scale as follows: zero absent, or not detected; one present, but less than 10% cover; two well represented, greater than 10% but less than 50% cover; three dominant vegetation type, more than 50% cover.

An algorithm developed by Chapman *et al.* (1989) was adapted to apportion relative percentages to the different primary vegetation types in a cell using all the attribute scores for that cell. The algorithm ensured that the coverage of each cell for the primary and secondary categories summed to 100% (100% cover being equivalent to 40,000 m^2). It was then possible to calculate the total area of coverage for each attribute and to combine attributes to fit specified definitions of heathland (Chapman *et al.*, 1989). The algorithm was implemented as a FORTRAN 77 program. Initially the program was run using only the primary categories for each of the three Dorset Heathland Surveys. When this program was run three errors were discovered in the 1978 dataset. Each of these errors was the result of the sum of a cell exceeding 100% coverage. In order to rectify this, the original paper survey sheets were examined to see if a clerical error during computer entry was at fault, and this was found to be

Table 3.3. The algorithm used to estimate areas from the scores for the percentage cover of each attribute in each grid square (adapted from Chapman *et al.* (1989))

(1.) Area of whole 200m x 200 m square = T = 4 ha

Assume for a particular square that for the primary vegetation category there are :

N_1 scores for 1   0 < % cover = 10

N_2 scores of 2   10 < % cover = 50

N_3 scores of 3   50 < % cover

At most one score of three is allowed in a square ($N_3 = 1$)

Let A_1, A_2, A_3 denote the estimated area represented in this square by scores of 1, 2 and 3 respectively.

(2.) Each score of 1 is set equal to 5% of the square

i.e. $A_1 = 0.05 \times T$

Then $R = T - N_1 \times A_1$ = Area of square covered by vegetation types with scores of 1 and/or 3

(3.) Case of $N_2 > 0$ and $N_3 = 0$. This occurs when no one vegetation type has < 50% cover. The area R is divided among the two scores:

Let $A_2 = R/N_2$

(4.) Case of $N_2 = 0$ and $N_3 = 1$. All of the remaining area R is assumed to be of the one most abundant vegetation type

Let $A_3 = R$

(5.) The cases left are those with one score of three and one or more scores of 2. The % cover represented by a score of 3 was assumed to be at least 55% of the grid square.

(6.) Case of $N_2 + 1$. In such cases N2 never exceeded 4.

Let $A_3 = 0.55 \times T = 2.2$ ha

and $A_2 = (R - A_3)/N_2$

(7.) Case of $N_2 = 1$ and $N_3 = 1$. The value of 2 and 3 scores depends on the area R% not covered by the N_1 vegetation types with a score of 1.

If $N_1 = 0$ so R% = 100 let A_2 = 30% and A_3 = 70%

At most $N_1 = 6$ so that R% = 70, in which case let A_3 = 55% (minimum allowed) and let A_2 = R% - A_3 = 15%. The intermediate situations were calculated by interpolation between these two extremes as follows:

N1	0	1	2	3	4	5	6
R%	100	95	90	85	80	75	70
A3	70	67.5	65	62.5	60	57.5	55
A2	30	27.5	25	22.5	20	17.5	15

the case. The dataset was corrected using the raw data sheet and the program run again. Three datafiles resulted, each containing the proportional areal coverage of each of the nineteen primary categories per cell for 1978, 1987 and 1996.

A similar process was carried out for the secondary categories. The program to run the algorithm was altered slightly because the combined secondary categories, which make up each of the primary categories, had to sum to 100%. No errors were identified in the datasets. Again, three datafiles resulted, each containing the proportional areal coverage of each of the secondary categories per cell for 1978, 1987 and 1996.

Potential errors in a dataset of this type, include those which occurred during the field survey and data entry stages. However, precautions taken by ITE during the survey and preparation of the data (including, staff training, quality control, data checking during input), have minimised error. However, given the nature of the data (primarily, the coarse numerical resolution of the classes) it is clear that some uncertainty remains. In particular, coverages may not always be an accurate representation of reality.

Thus, two sets of data resulted. The first, containing the proportional coverages of the primary categories on a per-pixel (cell) basis and the second, the proportional coverages of the secondary categories on a per-pixel (cell) basis. The nineteen primary categories provided a complete description of each pixel (cell) with their cover values summing to 100%; while the secondary categories provided a more detailed description of each primary category. The data could thus be imported into a Geographical Information System (GIS) (in this case, Arc/Info) to examine the long-term trends in the heathland landscape of Dorset between 1978 and 1996.

3.3 GIS Analysis

Spatial entities and their attributes may be stored using one of several spatial data models. These are most commonly, the *raster* data model and the *vector* data model (Chapter 2, 2.7.2). The raster data model is the simpler of the two and is based on the division of reality into a regular grid of identically shaped cells. Each cell is assigned a single value (ID) which represents the attribute for the area of that cell. It was necessary to choose a suitable data model for the GIS analysis. As the survey data was based on a grid (the National Grid subdivided into 200 m x 200 m pixels), it was logical that the data should be converted to a raster 'grid' format in Arc. Every primary and secondary category was, therefore, converted from a point coverage to a grid coverage.

3.3.1 Defining and creating patches of heathland

Heathland managers generally require information about patches rather than pixels of heath as the patch is the normal unit of management. Therefore, an object-based approach was adopted

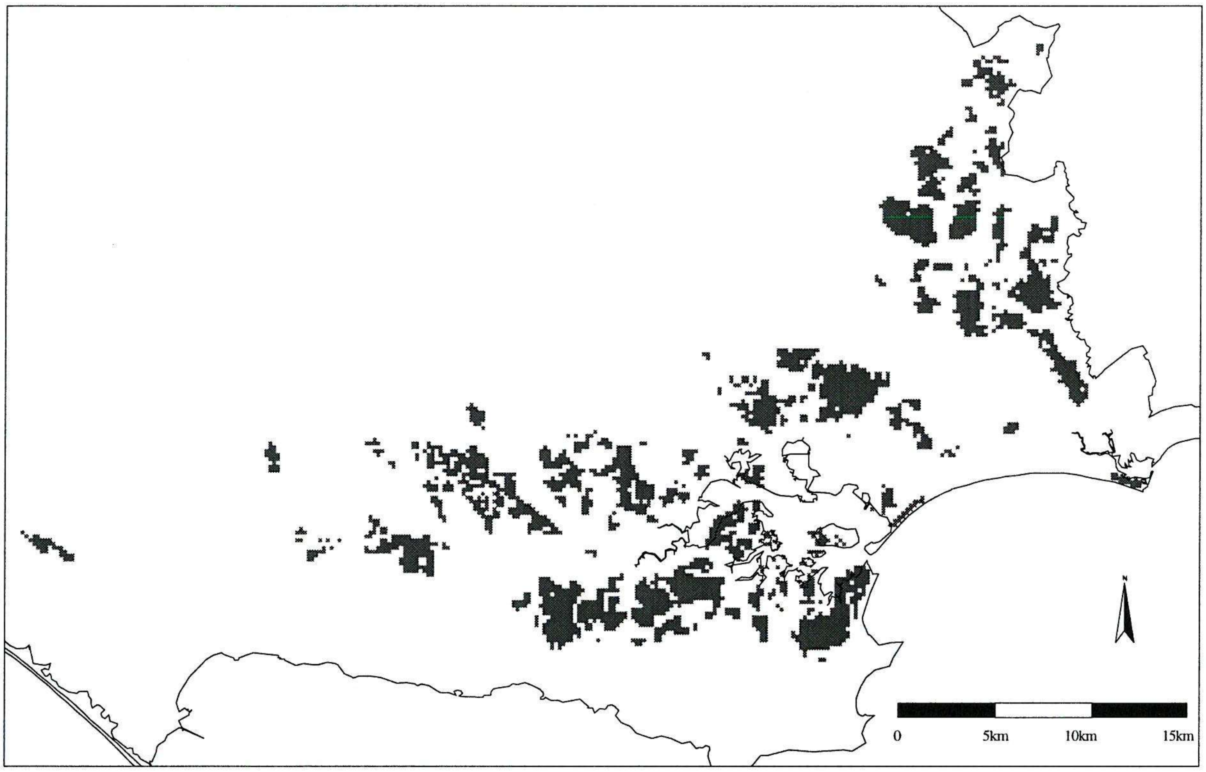


Fig. 3.4 Patches created using pixels containing any area of heath and a nearest neighbour index of eight

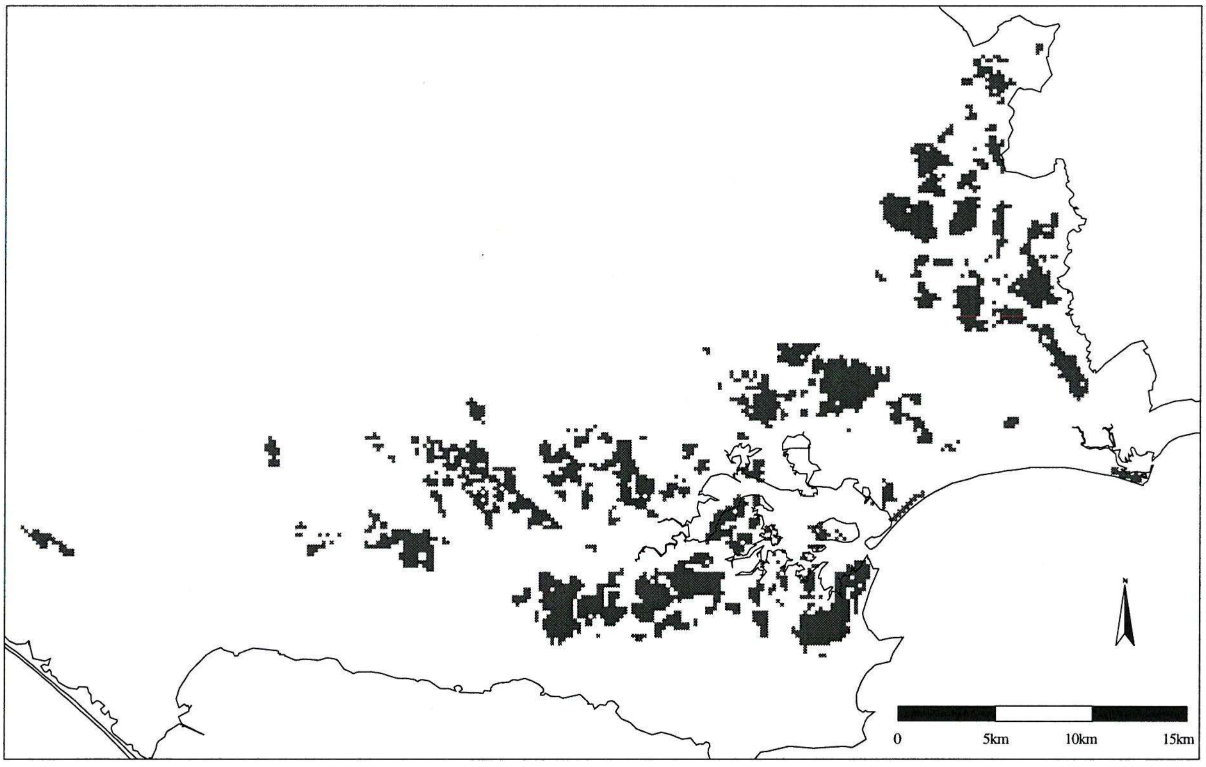


Fig. 3.5 Patches created using pixels containing any area of heath and a nearest neighbour index of four

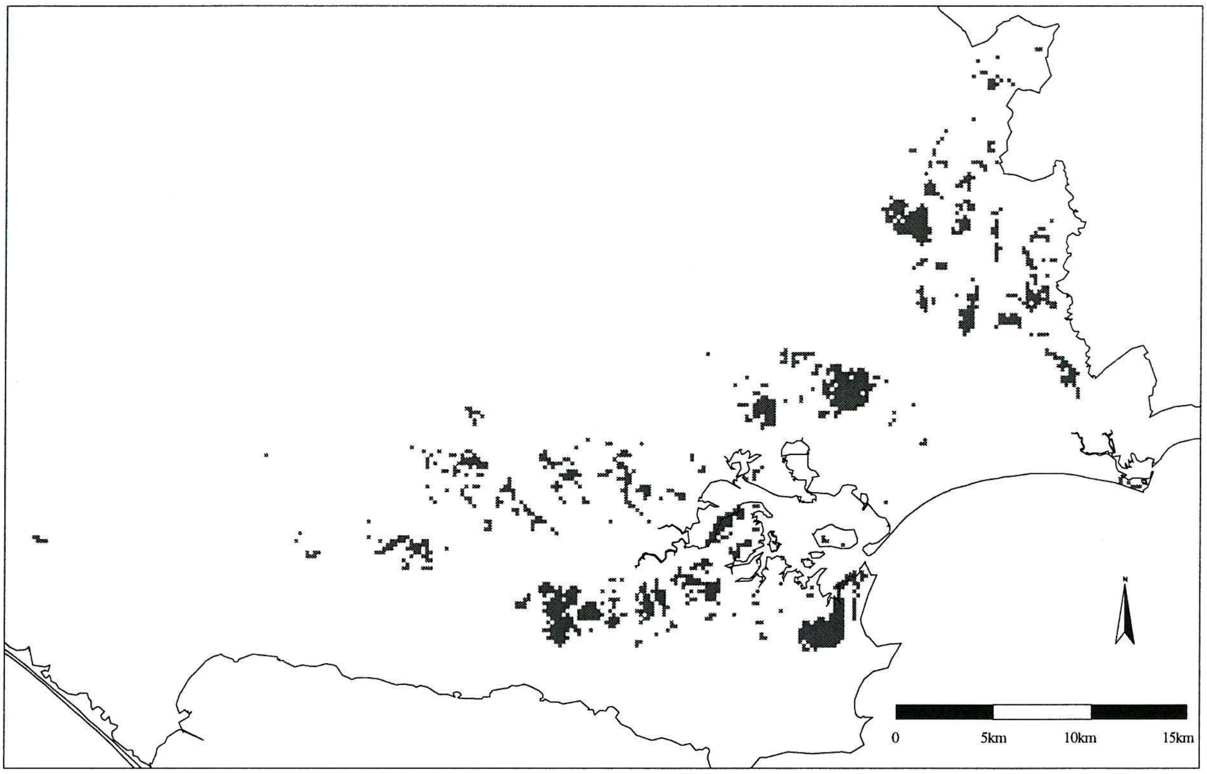


Fig. 3.6 Patches created using pixels containing over 50% heath and a nearest neighbour index of eight

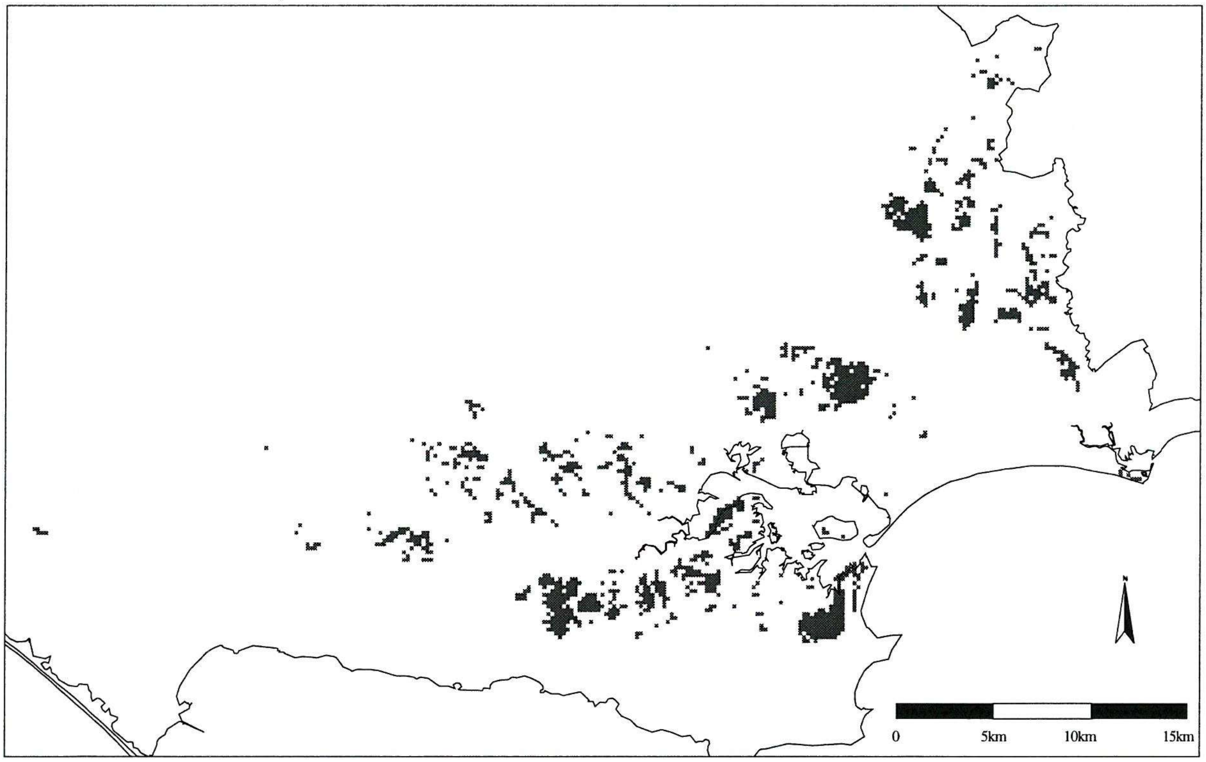


Fig. 3.7 Patches created using pixels containing over 50% heath and a nearest neighbour index of four

to group both the individual pixels and their attributes (in this case total heathland) into higher-order objects (patches of heathland).

The initial step in this process was to define heath for the purposes of this study. Heath was, therefore, deemed to be a combination of four primary categories: dry heath, wet heath, humid heath and peatland. The raster grid coverages of these four primary categories were combined to form a total heathland category. Scrub, carr and wood were also aggregated to form an invasive species category. The remaining twelve primary categories were aggregated to form an 'others' category.

Patches of heath were created using a nearest neighbour index in the GIS. Each cell of heathland was examined in turn. If a pixel containing the attribute total heathland existed either above, below or on either side of the selected cell (including diagonals) it was combined with the original cell to form a patch of heathland, each patch having a unique identifier. In total, 116 patches of heathland were created in this way in 1978 (Figure 3.4). This is a different approach to that taken by Chapman *et al.*, (1989) who joined together cells on the diagonal only if the cells contained over 75% heath. However, it was felt to be the best reflection of the patches of heathland in reality as only pixels containing heath were surveyed. If two neighbouring pixels contain heath, there is a reasonable chance that the pixels form part of the same patch.

A number of different rules were employed to create the patches (Figures 3.5-3.7), including that used by Chapman (1989). 152 patches were created when a nearest neighbour index of four was utilised, with diagonals not included. 224 patches resulted from using the same nearest neighbour index of four, but for pixels containing 50% heath. 156 patches were created using a nearest neighbour index of eight but for pixels containing 50% heath.

Histograms were plotted of patch area and number to give further insight into the effect of the differing patch creation rules outlined above (Fig. 3.8). The most noticeable difference between the histograms was variation in the number of smallest patches. When a nearest neighbour index of eight was used to amalgamate pixels containing any area of dwarf shrub vegetation, approximately eighty small patches resulted (Fig. 3.8 a). This figure rose to over 100 when a nearest neighbour index of four was utilised (Fig. 3.8 b) and remained relatively unchanged when the same nearest neighbour index was used but for pixels containing over 50% heath (Fig 3.8 c). However, the number of small patches rose to approximately 170 when a nearest neighbour index of eight for pixels containing 50% heath was used (Fig. 3.8 d). The variation in number of smallest patches meant that the mean patch size also varied: from 1.06 km^2 in Figure 3.8 a to 0.81 km^2 in Figure 3.8 b to 0.34 km^2 in Figure 3.8 c and finally to 0.24 km^2 in Figure 3.8 d. The number of larger patches remained relatively unchanged irrespective of the rules used for their creation

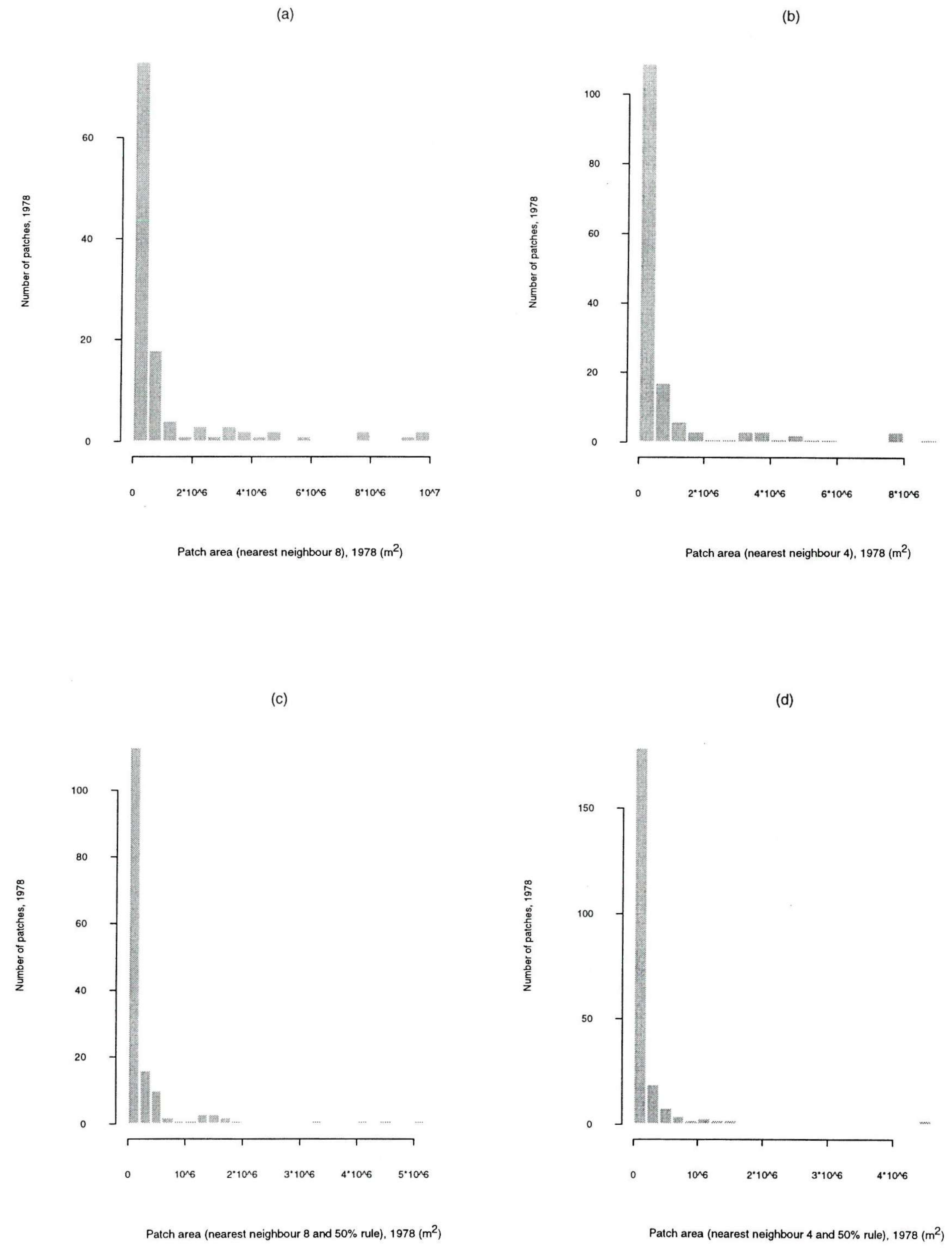


Fig. 3.8 Histograms of (a) area of patches, 1978 (m^2) created using a nearest neighbour index of eight for pixels containing any area of heathland; (b) area of patches, 1978 (m^2) created using a nearest neighbour index of four for pixels containing any area of heathland; (c) area of patches, 1978 (m^2) created using a nearest neighbour index of eight for pixels containing over 50% heathland; (d) area of patches, 1978 (m^2) created using a nearest neighbour index of four for pixels containing over 50% heathland.

By analysing both the maps and histograms of the patches created by each rule, it was decided to create the patches for this analysis by combining any pixels of heath including those on the diagonals. This method appeared to produce the best and most parsimonious reproduction of reality based on the understanding that only cells containing heathland were surveyed. This set of patches was retained to analyse the 1987 and 1996 data.

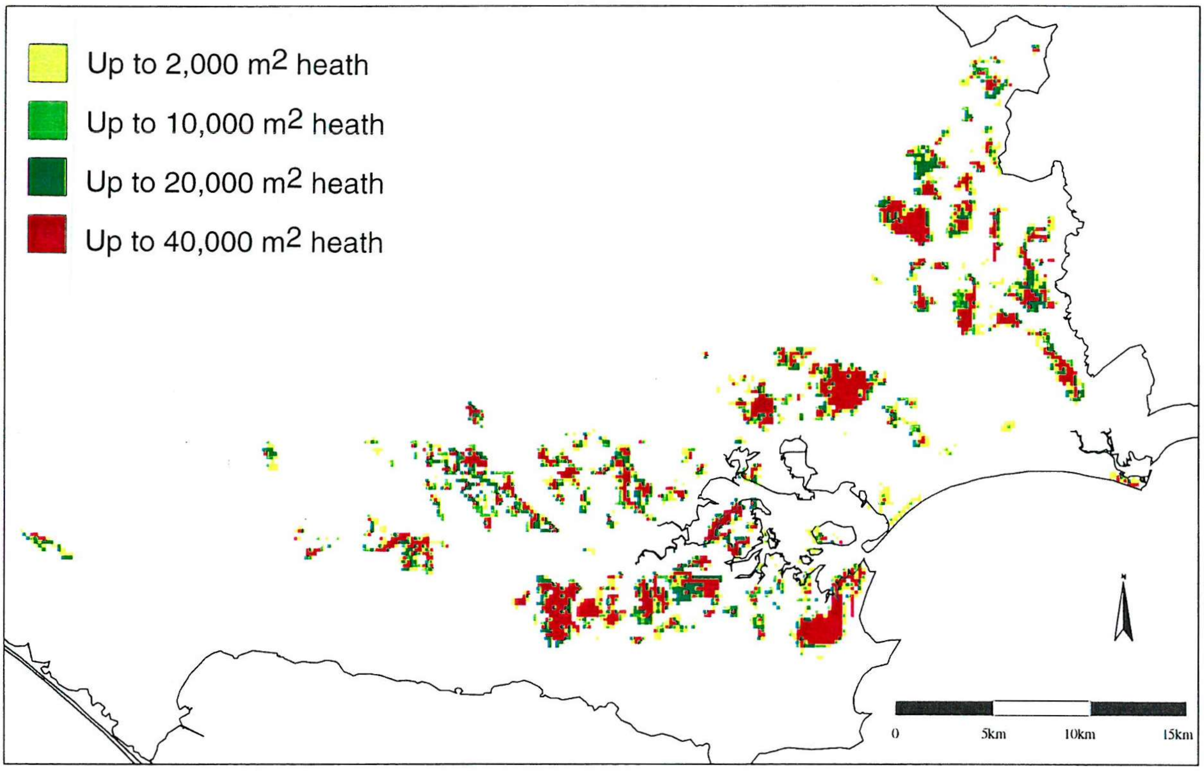


Fig. 3.9 Area of heath in a 200m x 200m pixel, 1978

3.3.2 The area of dwarf shrub vegetation

The area of dwarf shrub vegetation in a patch or survey pixel was the focus of this research. Further, when plotted, the area of dwarf shrub vegetation provided some insight into whether the patches created for use in this analysis adequately reflected any natural processes taking placing in the dwarf shrub vegetation. From the literature (Chapter 2, 2.3) it seemed that larger patches should have a central core composed almost totally of dwarf shrub vegetation which is less susceptible to change. With increasing proximity to the edge, the area of dwarf shrub vegetation lessens and edges contain little dwarf shrub vegetation and edge effects come into play. Therefore, the area of dwarf shrub vegetation in 1978 was mapped to provide an insight into whether the 116 patches created formed a reasonable basis for an analysis of the processes of change.

When the area of dwarf shrub vegetation in a pixel in 1978 was mapped, larger patches did appear to have a core entirely composed of dwarf shrub vegetation (Fig. 3.9) and the area of dwarf shrub vegetation lessened with increasing proximity to the edge. This was anticipated based on current understanding of dwarf shrub vegetation dynamics in a fragmented environment. Edge pixels are more susceptible to change as they may lie closer to non-dwarf shrub vegetation types. Smaller clusters of pixels contained smaller areas of dwarf shrub vegetation. Therefore, the patches created using the 1978 data reflected the sort of environment described in the literature. This was an important result as the patches were used as a template for the 1987 and 1996 data.

3.3.3 Contextual data

The Dorset Heathland Surveys comprised cells of 200 m x 200 m which contained (or had previously contained) heathland. The surrounding non-heath vegetation was not considered unless it fell within a cell. The use of remotely sensed data enabled the patches of heathland to be placed in the context of the surrounding land cover. Such a synoptic view is, according to Veitch *et al.*, (1995), invaluable when formulating management strategies that consider the landscape as a whole and not just the biotope of interest. Also, heathland patches do not exist independently of their surroundings (See Chapter 2, 2.3.1). Remotely sensed data from the Landsat MSS have been used to map the location and extent of the heathland biotope (Veitch *et al.*, 1995) and the environment surrounding such heathland. Ecological knowledge was used to guide the manipulation of remotely sensed imagery to provide contextual data for a patch. Satellite remote sensing has been much used in the UK to map semi-natural vegetation (Weaver, 1984; O'Hare, 1987; Williams, 1987; Fuller & Parsell, 1989; Belward e*t al.*, 1990 and Baker e*t al.*, 1991). The Landsat Thematic Mapper (TM) is generally considered to provide the best combination of radiometric and geometric properties currently available for studies of semi-natural vegetation and habitats (Veitch *et al.*, 1995). A remotely sensed TM image of Dorset from August 1984 was used in this instance to provide contextual data for heathland patches. The image was processed using ESRI's IMAGINE software. Initially, each of the seven bands of the image were imported separately into Imagine 3.8 and then combined to form a complete image. The image was geometrically corrected using approximately 40 ground control points (GCP). Once corrected the root mean square (RMS) error was calculated to check the accuracy of the geometrically rectified image. The RMS error was less than a single pixel which was satisfactory.

As the image was a complete TM scene, much of it was unnecessary. Therefore, the image was subsetted such that the image area covering Hampshire, and the Isle of White were removed. The remaining image covered Dorset in its entirety and little else. Next, the image was classified, as it was necessary to group pixels in the image into classes which were more meaningful than the original digital number values. An unsupervised classification was used first to identify spectrally distinguishable clusters present. These were then compared with known areas on the ground (aerial photos of Middlebere Heath and OS Map data were used as a comparison). Following this comparison, a set of training data were produced for use in supervised classification. The supervised classification used only those classes which were identified spectrally and only those wavebands which helped to separate the classes. The supervised classification produced a number of land cover classes which were labelled as wood, scrub, water and heath, as well as several land use classes including agriculture, grassland, bare ground and urban land. Since, succession was the interest only the land cover classes were relevant. Further, a classification accuracy assessment indicated the classification was 81% accurate (kappa = 0.69). The image was re-sampled to force the pixels in the image to match those in the GIS. The pixels (originally 30 m x 30 m) were resampled to become 200 m x 200 m pixels.

The classified image was imported into Arc/Info and converted to a grid. The image was used to provide contextual information for each patch. However, only a certain radius around each patch was necessary to provide the contextual information required. Therefore, each of the 116 patches (created using the 1978 data as a template) were expanded, initially by two pixels. The grid containing the 116 patches was used to mask out the original patches. The result was a grid containing just the expanded parts of the patches. This new grid was used to mask the image. The resulting grid contained an outline of every patch, two pixels wide and made up of the data from the remotely sensed image. This process was repeated and the patches were expanded by four pixels. The resulting data indicated which land cover class or classes surrounded a patch. The GIS was used to assess the areal coverage of woodland and shrub surrounding each patch facilitating an analysis of the effect of area of invasive species surrounding a patch on percentage change in area of heath. Therefore, a surrogate variable for context was available for use in the analysis of change. The other variables are outlined in Section 3.5.

3.4 Management Data

Heathland management techniques were outlined in Chapter 2.2.3. However, the use of such techniques in Dorset was not reviewed. It has been stated previously that the aim of this research was to build a predictive, statistical model of the spatial dynamics (change) of the heathlands of Dorset. However, a distinction must be drawn between natural change and human-induced change over time. Data on heathland management carried out in Dorset were, therefore, a necessity in drawing this distinction. Management data were obtained for the heathlands of Dorset in their entirety. These data were used to select patches of heath which had been subjected to management between 1978 and 1996. This allowed not only an examination of the consequences of differing management practices on the heaths, but more importantly, it allowed the uncertainty in the per-patch analysis of ecological dynamics to be reduced.

3.4.1 Management and conservation of the Dorset heaths

The most extensive heathland management projects did not commence until after the second Dorset Heathland Survey (1987) results were published, making the heathland managers aware of quite how precarious the survival of the heathlands had become. Two factors were identified as the cause of changes in the Dorset heaths (Webb, 1990). First, there were direct losses. Such losses were caused by conversion of heathland to farmland and forestry and to urban and industrial development. This type of direct loss had virtually stopped between 1987 and 1996 due to planning and environmental legislation, and due to the withdrawal of farming subsidies. Second, there were losses caused by the succession of heath to scrub and woodland. This type of loss is the result of a cessation in traditional management practices (for example, grazing and burning). The marked increase in scrub and trees (15% between 1978 and 1987) led to the implementation of large programmes of conservation management (Auld *et al.*, 1992; Woodrow *et al.*, 1996; Rose *et al.*, in press).

3.4.2 Acquiring the management data

The main aims of the conservation projects in Dorset are primarily the rehabilitation of degraded heathland, to expand the area and to ensure its ecological diversity and sustainability. So far these aims are being achieved mainly by the removal of invading species such as gorse, scrub and bracken. At present there are over ten different Government and Charitable bodies actively managing different areas of the heaths (Table 3.4) without collusion. This made the collection of data concerning heathland management an arduous and time consuming task.

Initially, any organisation which carried out any heathland management was identified and then contacted. Meetings took place with each organisation to ascertain the types and degree of management being carried out. Records of each organisation's activities were examined and the relevant data extracted. Since the Dorset Heathland Surveys were carried out in 1978, 1987 and 1996, the management data were divided into two categories:

1. 1978 and 1987 heathland management
2. 1987 and 1996 heathland management

The majority of the management practices were recorded on a standard project recording sheet with a map attached, indicating the precise area of management. Although the records were clear, the maps were quite often not. Many of the maps were very roughly drawn maps with no scale, grid references nor even a North bar included. This made pin-pointing the exact location and scale of many managed areas difficult. Such problems were overcome by drawing every pixel surveyed in the initial Dorset Heathland Survey (1978) onto the relevant 1:25,000 Ordnance Survey (OS) map. The next step involved highlighting each area managed by each organisation (not the individual management site, but the entire heath). Once this had been achieved, a copy of the Arc/Info coverage of each pixel surveyed (again using the 1978 survey) was magnified to A0 size. This map of survey pixels was used to record the type of management carried out in each 200 m x 200 m pixel. Two such maps were produced, the first for management carried out between 1978 and 1987 and the second, for management carried out between 1987 and 1996.

Table 3.4 Areas of managed heathland throughout Dorset.

Organisation	Area managed	Dates managed
Herpetological Conservation Trust	Trust sites and a number of areas for other organisations	1971 to present
Dorset Wildlife Trust	Trust Nature Reserves and some small other areas	1970s to present
English Nature	Nature Reserves - limited in other areas	1970s (on some Reserves) to present
RSPB	Managed sites for other organisations	1988 to present
RSPB Nature Reserves	Arne and Stoborough	approx. 1977 to present
Poole Borough Council	Tiny parts of Canford heath, nothing substantial	1988 - 1991
Dorset County Council	Merrytown Heath (Herne Common SSSI)	1989 to present
	Sopley Bog (Udden Heath SSSI)	1992 to present
	Turnerspuddle	
	Alder Heath Country Park	1994 to present
	(part of Herne) but RSPB & DWT have Stewardship for last three years	1974 to present
Forest Enterprise and the Forestry Commission	Most Forestry Commission and Forest Enterprise sites across Dorset	approx. 1987 to present
East Dorset Council	Stephen's Castle, Dewlands Common, Parley Common and others	approx. 1987 to present
Christchurch Borough Council	St Catherines Hill	1987 to present
Bournemouth Borough Council	Turbary Common and Kinson Common	1988 to present

Eventually, each area managed was located on the OS maps and the corresponding pixel was located on the pixel-based map of the heaths. A colour key was created, each management practice having a different colour associated with it. The management type was then entered in the relevant pixel of the pixel-based map. When all the management data had been recorded in this way, a management database was built. Two datafiles were created, one for each survey category. The data formed two main columns, the first being an ID to relate the pixel ID to the relevant co-ordinate, the second being a single numeric indicating whether or not that pixel was managed. The number one indicated the pixel was unmanaged, two indicated the pixel was managed. The third column to the sixteenth column were also numeric, each number being a management type (see Table 3.5). It is important to realise that the management data were not complete. There are no data for the specific area of a pixel managed and no information such as the intensity of some management practices such as grazing.

Table 3.5 Numeric definition of management type.

Management Type	Management Code	Management Type	Management Code
Gorse coppicing	3	Bracken cutting	11
Foraged	4	Pine removal	12
Bracken spraying	5	Grazing	13
Scrub clearance	6	Sand patches created	14
Rhododendron clearance	7	Heather re-establishment	15
Controlled burning	9	Mowing	16
Wild fire	10		

3.4.3 Importing the management data into the GIS

The initial step in importing data into Arc was to create a template for the data. Therefore, two templates were created, one for the 1978 and 1987 data and one for the 1987 and 1996 data. The template took the from of sixteen columns, the first being an ID column, the second indicating whether or not the pixel was managed and the next columns indicating the type of management carried out for that pixel. The raw data were then 'added' to the template. The two new datafiles were then 'related' to the co-ordinate file (point coverage for 1978). The relation was based on the common ID which indicated which pixel was associated with which co-ordinate as well as whether or not the pixel was managed. Thus, a comprehensive database of heathland management in Dorset between 1978 and 1996 was developed. Patches which were managed could thus be removed from the analysis to examine purely natural change. Alternatively, the effect of the varying management practices on area of heath could also be examined to see how effective they truly were.

3.5 Defining the variables

With the patches of dwarf shrub vegetation having been created, the response variable and explanatory variables could be defined. It was necessary for the response variable to reflect the dynamics of the dwarf shrub vegetation accurately. The explanatory variables were based around a single ecological process: succession to scrub, carr and woodland (Chapter 2, 2.2.2). Several factors were hypothesised to influence change in area of dwarf shrub vegetation over time. These factors included edge effects, patch geometry, the area of dwarf shrub vegetation in a patch, the area of invasive species in a patch, the density of dwarf shrub vegetation in a patch, density of invasive species in a patch and context.

3.5.1 Defining the response variable

Several alternative response variables could have been chosen to analyse change. However, the response variable was defined as the percentage change in area of heathland between 1978 and 1987 (or between 1987 and 1996). The simple difference in area of heathland between 1978 and 1987 might have been plotted on the ordinate in place of the percentage change (see Appendix 1). However, percentage change was chosen because area of dwarf shrub vegetation was of interest as an explanatory variable. The rationale for selecting the percentage change is as follows: if we assume succession by invasion from the edge of the patch, and the rate of invasion is constant, larger patches will decrease in area more than smaller patches. However, if the initial area covered by several smaller patches were equal to the area covered by one larger patch the area lost would be greater for the smaller patches. Therefore, it is the percentage lost that is important, not the actual area lost. Further, the analysis aimed to examine the relationship between change and area. Using percentage change minimised correlation between the response variable and area. For these reasons, the variable to be explained was defined as the change in area of heathland between 1978 and 1987 as a percentage of the area of heathland in 1978.

3.5.2 Defining the explanatory variables

Once the response variable had been defined the next step was to define the explanatory variables. The explanatory variables were defined based on the properties identified as the most likely to influence percentage change in area of dwarf shrub vegetation (Chapter 2, 2.3.1). That is, variables (see Table 3.6) were chosen because they were deemed of most ecological relevance in a patchy environment and because it was hypothesised that each would have an effect on the percentage change in the area of dwarf shrub vegetation in a patch. Initially, fourteen explanatory variables were chosen based on the aggregated primary categories.

Heathlands are plagio-climax communities. Therefore, succession occurs continually unless the process is arrested by management. Succession does not depend solely on invasion from outside a patch of dwarf shrub vegetation. Additionally, the seedbank may play a rôle in succession from dwarf shrub vegetation to scrub or wood. The factors likely to result in change in area of dwarf shrub vegetation were divided into three. First, factors relating to the areal extent of dwarf shrub vegetation and invasive species both in a patch and in the edge of a patch. Second, factors relating to patch geometry and third, context.

It was hypothesised that percentage change in area of dwarf shrub vegetation was influenced by the area of dwarf shrub vegetation in a patch. Larger areas of dwarf shrub vegetation are in theory, less susceptible to change. If the rate of succession is constant then larger areas of dwarf shrub vegetation will involve smaller percentage change than smaller areas. Further, succession depends upon proximity to a seed source. The greater the areal extent of dwarf shrub vegetation in a patch, the fewer seed sources available within that patch and, therefore, change is less likely. Conversely, the larger the area of invasive species in a patch, the greater the pressure from succession and the greater the likelihood of a decline in area of dwarf shrub vegetation over time. Therefore, it was hypothesised that the greater the area of invasive species in a patch, the greater the percentage change (decrease) in area of dwarf shrub vegetation over time

It was hypothesised that percentage change was influenced by the density of dwarf shrub vegetation in a patch. Density described the area of dwarf shrub vegetation in a patch, relative to the area of a patch and indicated the degree of fragmentation within a patch. The more dense the coverage of dwarf shrub vegetation was across a patch, the less fragmented the patch was and the fewer edges open to invasion. It was clear from the literature that the greater the degree of internal patch fragmentation the greater the pressure from succession. A fragmented patch is in reality made up of several smaller patches and smaller patches are more susceptible to change. Further, it was hypothesised that percentage change was influenced by the density of invasive species in a patch. The null hypothesis being percentage change was not correlated with the density of invasive species. The more dense the coverage of invasive species, the greater the pressure from succession and the greater the percentage decrease in area of dwarf shrub vegetation.

It was clear from the literature (Chapter 2, 2.3.1) that edge effects play an important rôle in the process of succession. Therefore, edge effects were hypothesised to result in percentage change in area of dwarf shrub vegetation. As the area (or density) of dwarf shrub vegetation in the edge of a patch increased, it was hypothesised that (negative) percentage change would decrease. The smaller the area of invasive species in the edge of a patch the fewer seed sources available for invasion and pressure from succession declines. Conversely, it was hypothesised that the greater the area (or density) of invasive species in the edge of a patch, the greater the pressure from succession resulting in greater percentage decreases in area of dwarf shrub vegetation. As the area of invasive species in the edge of a patch increases, the proximity to invasive species increases and seeds rain down on the dwarf shrub vegetation resulting in extreme pressure from invasion.

The literature indicated that patch geometry influences change in a fragmented environment (Chapter 2, 2.4.1). Therefore, it was hypothesised that percentage change in area of dwarf shrub vegetation was related to patch geometry as patch geometry was likely to influence the

Table 3.6 Hypotheses tested using explanatory variables.

Heathland composition variables to test their influence on percentage change	**Defining each variable**	**Hypotheses tested**
1. Area of heath in patch	The area of heath in a patch was calculated by summing the area of heath in each pixel in a patch	The greater the area of heath, the smaller the decrease in heath as a percentage over time
2. Area of invasive species in patch	The area of invasive species in a patch was calculated by summing the area of invasive in each pixel in a patch	The greater the area of invasive species, the greater the decrease in heath as a percentage over time
3. Density of heath in patch (area/*c* x 40,000)	Density was calculated by dividing the area of heath in a patch by the number of pixels in that patch multiplied by 40,000 (the area of a pixel in m^2)	The greater the density of heath, the smaller the decrease in heath as a percentage over time
4. Density of invasive species in patch (area/*c* x 40,000)	Density was calculated by dividing the area of invasive species in a patch by the number of pixels in that patch multiplied by 40,000 (the area of a pixel in m^2)	The greater the density of invasive species, the greater the decrease in heath as a percentage over time
5. Area of heath in edge of patch	Each patch was shrunk by one pixel (in Arc/Info) and the shrunken grid used as a mask creating a new grid containing just the edge pixels in each patch. The area of heath in an edge was calculated by summing the area of heath in each pixel in an edge	The greater the area of heath in the edge, the less susceptible a patch is to change in area of heath as a percentage over time
6. Area of invasive species in edge of patch	Each patch was shrunk by one pixel (in Arc/Info) and the shrunken grid used as a mask creating a new grid containing just the edge pixels in each patch. The area of invasive species in an edge was calculated by summing the area of invasive species in each pixel in an edge	The greater the area of invasive species in the edge, the more susceptible a patch is to change in area of heath as a percentage over time
7. Density of heath in edge of patch (area/*c* x 40,000)	Density was calculated by dividing the area of heath in the edge of a patch by the number of pixels in the edge multiplied by 40,000	The greater the density of heath in the edge, the less susceptible a patch is to change in area of heath as a percentage over time
8. Density of invasive species in edge of patch (area/*c* x 40,000)	Density was calculated by dividing the area of invasive species in the edge of a patch by the number of pixels in the edge multiplied by 40,000	The greater the density of invasive species in the edge, the more susceptible a patch is to change in area of heath as a percentage over time
9. Ratio of area of heath:invasive species in patch	The area of heath in a patch was divided by the area of invasive species in the same patch to calculate a ratio	The greater the area of heath to invasive species, the smaller the decrease in heath as a percentage over time
10. Ratio of area of heath in edge:area of invasive species in edge of patch	The area of heath in the edge of a patch was divided by the area of invasive species in the same edge to calculate a ratio	The greater the area of heath to invasive species in the edge, the smaller the decrease in heath as a percentage over time
Geometric variables to test their influence on percentage change	**Defining the variables**	**Hypothesis tested**
11. Patch context	A remotely sensed image proved contextual information	The greater the area of invasive species surrounding a patch, the more susceptible a patch is to change in area of heath as a percentage over time
12. Area of patch (as opposed to area of dwarf shrub vegetation in a patch)	The area of a patch was calculated by multiplying the number of pixels in a patch by 40,000 (the area of a pixel)	The greater the area of the patch, the less susceptible it is to change
13. Length of the perimeter of patch	Perimeter was calculated by multiplying the number of pixels in the edge of a patch by 200 (the length of a pixel)	The longer the perimeter, for a fixed heath area the more susceptible the patch is to change
14. Shape of patch ((*c* x 40,000)/perimeter)	Shape was calculated by dividing the area of a patch by the perimeter	The more round the patch, the less susceptible the patch is to change

Where c = count

process of succession. It was hypothesised that the area of a patch influenced percentage change for reasons similar to that of area of dwarf shrub vegetation (larger patches being less susceptible to change if the rate of succession was assumed to be constant). It was hypothesised that the perimeter of a patch influenced change. Specifically, the longer the perimeter (for a fixed patch area), the greater the influence of edge effects resulting in increased pressure from invasion and, therefore, increased percentage change. Shape too can influence succession. It was hypothesised that more rounded (disc-shaped) patches were less susceptible to change than more elongated patches if the rate of succession was constant. In all, the explanatory variables were chosen to indicate what factors influenced percentage change in area of dwarf shrub vegetation over time.

3.5.3 Primary category variables

Several primary category explanatory variables were chosen to examine the relationship between percentage change in area of dwarf shrub vegetation type and the area, density, context etc. Indeed, the explanatory variables selected for the primary category analysis were mirrored those selected as aggregated primary category explanatory variables. However, instead of using the area of dwarf shrub vegetation in a patch, if percentage change in area of dry heath was of interest, then the area of dry heath in a patch was chosen as an explanatory variable (see Table 3.7 for a complete listing). As with the aggregated primary category variables, the explanatory variables were defined based on the properties identified as the most likely to influence percentage change in area of dwarf shrub vegetation (Chapter 2, 2.3.1). As outlined above (see Section 3.5.2), the variables were chosen because they were deemed of most ecological relevance in a patchy environment and because it was hypothesised that each would have an effect on the percentage change in the area of dwarf shrub vegetation type in a patch. The hypotheses tested reflected the aggregated primary category hypotheses exactly.

The patches created based on the presence or absence of dwarf shrub vegetation in a pixel remained unaltered for the primary category analysis. Each dwarf shrub vegetation type may change at a unique rate however, each dwarf shrub vegetation type is not discrete from other dwarf shrub vegetation types. By taking this approach, some of the chosen explanatory variables, particularly, the explanatory variables relating to patch geometry, may not necessarily reflect reality. Despite this drawback, the primary category explanatory variables remained almost unaltered. The explanatory variables relating to patch geometry were removed. If the area of for example, peatland in a patch was small, then it could not be hypothesised that percentage change would be affected by patch geometry.

Table 3.7 Primary category explanatory variables based on a single dwarf shrub vegetation type (in this case dry heath), percentage change in area of dry heath being the response variable

Explanatory variable	Explanatory variable
Area of dry heath	Area of heath:dry heath
Area of scrub	Area of heath:scrub
Area of carr	Area of heath:carr
Area of woodland	Area of heath:woodland
Density of dry heath	Density heath:dry heath
Density of scrub	Density heath:scrub
Density of carr	Density heath:carr
Density of woodland	Density heath:woodland
Area of dry heath in edge	Area of heath:dry heath in edge
Area of scrub in edge	Area of heath:scrub in edge
Area of carr in edge	Area of heath:carr in edge
Area of woodland in edge	Area of heath:woodland in edge
Patch context	Density heath:dry heath in edge
Density of dry heath in edge	Density heath:scrub in edge
	Density heath:carr in edge
	Density heath:woodland in edge
Density of scrub in edge of patch	
Density of carr in edge of patch	
Density of woodland in edge of patch	

3.5.4 Secondary category explanatory variables

A series of secondary category explanatory variables were chosen to examine the relationship between percentage change in area of dwarf shrub vegetation (and dwarf shrub vegetation type) and several invasive species (Table 3.8). The secondary category explanatory variables scaled down the analysis to the species level. Secondary category explanatory variables were chosen to examine if the rate of succession varied for different invasive species types. Each hypothesis was the same. As the area of an individual invasive species type increased so would percentage change. Succession depends on the proximity to a seed source and, therefore, the greater the coverage of an invasive species, the greater the pressure from succession.

Table 3.8 Hypotheses tested based on secondary category explanatory variables

Heathland composition variables to test their influence on the rate of succession	Hypotheses tested
1. Area of *Pteridium* in a patch	As area increased percentage change increased
2. Area of *Alnus* in a patch	As area increased percentage change increased
3. Area of *Betula* in a patch	As area increased percentage change increased
4. Area of *Pinus* in a patch	As area increased percentage change increased
5. Area of *Ulex europaeus* in a patch	As area increased percentage change increased
6. Area of *Rhododendron* in a patch	As area increased percentage change increased
7. Area of *Salix* in a patch	As area increased percentage change increased
8. Area of *Quercus* in a patch	As area increased percentage change increased
9. Area of conifers in a patch	As area increased percentage change increased
10. Area of *Sarothamnus* in a patch	As area increased percentage change increased
11. Area of *Ulex gallii* in a patch	As area increased percentage change increased
12. Area of mixed deciduous woodland in a patch	As area increased percentage change increased

3.5.5 Alternative explanatory variables

Several other explanatory variables were chosen for inclusion in the analysis. However, these explanatory variables were not hypothesised to cause natural ecological change. Unlike succession, land use change is not a natural process resulting in natural ecological change. The area and density of 'others' were included as explanatory variables when it became clear that changes in land use resulted in change in area of dwarf shrub vegetation (Table 3.9). However, the focus of the analysis remained on the relationship between percentage change and natural change rather than anthropogenic change.

This analysis was concerned with natural ecological change however, it was clear from previous analyses that changing land use resulted in substantial decreases in area of dwarf shrub vegetation (Webb & Haskins, 1980; Webb, 1990 & Veitch, *et al.*, 1995). Therefore, it seemed reasonable to examine the effect of land use change on change in area of dwarf shrub vegetation without shifting the focus away from natural change. Indeed, the effect of land use change cannot easily be predicted as it is not a function of the initial state of a patch. Explanatory variables based on the area and density of land use types were included in the analysis (Table 3.9). Density reflected the degree of internal patch fragmentation caused by land use. Density of 'others' in the edge reflected the peripheral fragmentation of a patch.

Table 3.9 Alternative explanatory variables not hypothesised to be related to natural changes in dwarf shrub vegetation (or dwarf shrub vegetation type).

Explanatory variables	
1. Area of 'others'	13. Density of dry heath
2. Density of 'others'	14. Density of wet heath
3. Area of 'others' in edge	15. Density of humid heath
4. Density of 'others' in edge	16. Density of peatland
5. Area of heath : 'others'	17. Area of dry heath in edge
6. Density of heath : 'others'	18. Area of wet heath in edge
7. Area of heath : 'others' in edge	19. Area of humid heath in edge
8. Density of heath : 'others' in edge	20. Area of peatland in edge
9. Area of dry heath	21. Density of dry heath in edge
10. Area of wet heath	22. Density of wet heath in edge
11. Area of humid heath	23. Density of humid heath in edge
12. Area of peatland	24. Density of peatland in edge

The influence of dwarf shrub vegetation types on change in other dwarf shrub vegetation types was also examined (Table 3.9). It had been hypothesised that change in area of a particular dwarf shrub vegetation type (for example, dry heath) would be affected by the area of dry heath in a patch. However, the relationship between percentage change in area of dry and the area of each of the other dwarf shrub vegetation types was also examined. The area of wet heath in a patch was unlikely to affect the rate of succession however, it could influence percentage change in area of dry heath. Further, previous analyses of the data identified fluctuations between dwarf shrub vegetation types (for example, Rose *et al.*, 1999). Therefore, the influence of these fluctuations on percentage change was examined.

3.6 The area of dwarf shrub vegetation

It was the area of dwarf shrub vegetation in a patch or survey pixel which was the focus of this research. Therefore, the area of dwarf shrub vegetation in 1978, 1987 and 1996 was mapped to illustrate the changing spatial coverage of dwarf shrub vegetation between the three surveys.

When the area of dwarf shrub vegetation in a pixel in 1978 was mapped (Fig. 3.9), larger clusters of pixels appeared to have a core entirely composed of dwarf shrub vegetation. The edges of these clusters of pixels contained smaller densities of dwarf shrub vegetation. It may be that edge pixels were more susceptible to change as they are likely to lie closer to non-dwarf shrub vegetation types. Smaller clusters of pixels contained smaller areas of dwarf shrub vegetation.

In 1987 there was little change although at first there appeared to be some change (Fig. 3.10). The increase in pixels which contained little dwarf shrub vegetation resulted partly from a large number of extra pixels being surveyed in 1987. The area of dwarf shrub vegetation did clearly decline in some pixels. When the area of dwarf shrub vegetation in a pixel in 1996 was mapped (Fig. 3.11) there were clear changes from the previous two maps. The area of dwarf shrub vegetation declined in the majority of pixels. The change was very dynamic occurring across single isolated pixels and clusters of pixels. The core pixels (that is, pixels which lay in the center of a cluster of pixels and were composed almost entirely of dwarf shrub vegetation) had remained relatively stable in 1978 and 1987. However, in 1996 the area of dwarf shrub vegetation in such pixels declined.

The dwarf shrub vegetation of Dorset was relatively stable in 1978 and 1987 but not between 1987 and 1996. In 1996 core pixels previously comprised of dwarf shrub vegetation alone were not so any longer. There was no obvious reason for the sudden wide scale decline in dwarf shrub vegetation although succession may be exponential and may have accelerated between 1978 and 1987.

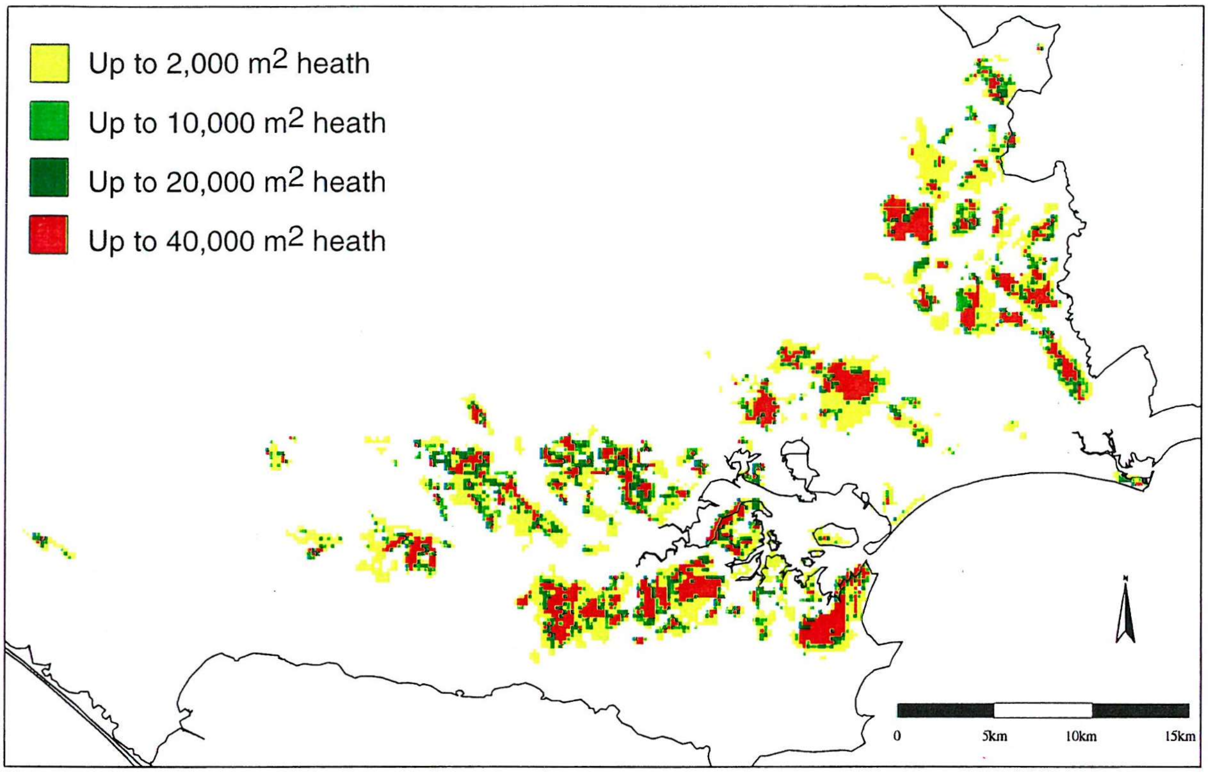


Fig. 3.10 Area of heath in a 200m x 200m pixel, 1987

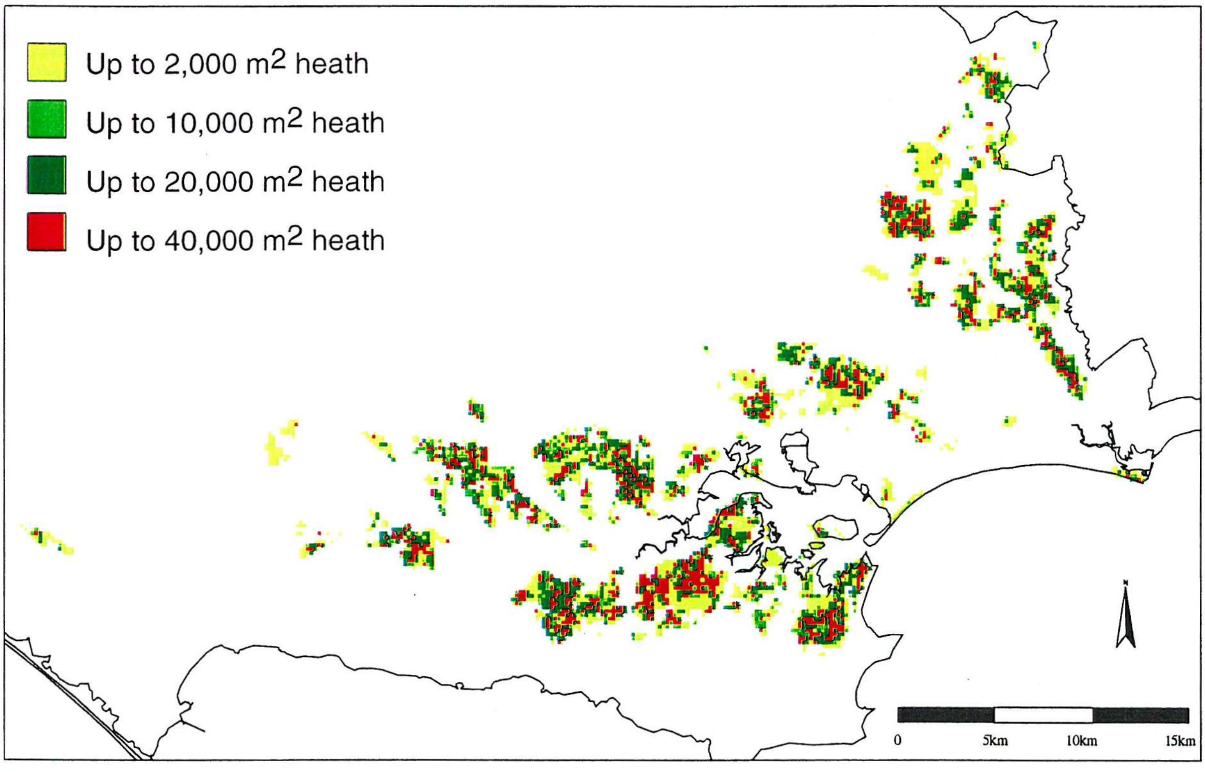


Fig. 3.11 Area of heath in a 200m x 200m pixel, 1996

3.7 Summary

The heathlands of Dorset are a unique environment sustaining a wealth of diverse populations of both flora and fauna. Further, the geology of Dorset has influenced the development of the wealth of flora and fauna found there. However, it is clear that they are an environment under threat. The Institute of Terrestrial Ecology carried out three Dorset Heathland Surveys which provided a baseline for monitoring change. The surveys examined the presence (or absence) of a variety of species, land cover and land use types in a series of 200 m by 200 m cells. Areal coverage was recorded on a scale of zero to three. The survey data were divided into aggregated primary and primary categories and an algorithm transformed the data from scores of between zero and three to areal coverages. The algorithm ensured the coverage of each cell summed to 100%. A GIS was used to define patches of dwarf shrub vegetation. Contextual data for each patch were acquired from a remotely sensed image. Management data were collected and a database of management activities created. Finally, the response variable and explanatory variables were chosen as the initial step in the modelling procedure. The response variable was percentage change in area of dwarf shrub vegetation. The explanatory variables were chosen as the factors most likely to influence the process of succession and, therefore, result in percentage change in area of dwarf shrub vegetation. The area of dwarf shrub vegetation in 1978, 1987 and 1996 was mapped as this was the variable of most interest. These maps provided the first insight into the spatial structure of change in the area of dwarf shrub vegetation between 1978 and 1996. The next step was to examine the relationship between the response variable and each independent variable. Regression will be used to build a predictive model of the resulting significant relationships.

CHAPTER 4

PATCH-BASED ANALYSIS

4.1 Introduction

In this chapter, a patch-based perspective was taken to analyse change in area of dwarf shrub vegetation. The analysis presented in this chapter comprises several stages. First, overall areal change in dwarf shrub vegetation over time was examined. Second, a univariate analysis of some of the data was carried out. Third, a spatial element was added by mapping change. Fourth, the strength of the relationship (correlation) between percentage change and each explanatory variable was examined. Finally, a statistical model of change was developed using both simple regression and multiple regression modelling techniques (see Chapter 2, 2.4.3).

4.2 The patch-based perspective

The patch dynamics perspective was taken because dwarf shrub vegetation (like most vegetation) tends to exist as patches (a grouping of dwarf shrub vegetation species), rather than as single isolated plants. Physical and ecological disturbances in the landscape produce patches, discrete communities in an area of dissimilar community structure or composition (Pickett & White, 1985). The dwarf shrub vegetation of Dorset forms patches in a matrix of forest agricultural and urban land. Therefore, it is reasonable to expect that processes such as succession occur at a patch scale. That is, it is reasonable to expect that succession occurs from outside a dwarf shrub vegetation patch and invades inwards.

Several other factors further support the adoption of a patch-dynamics perspective to model dwarf shrub vegetation dynamics in Dorset. Patch dynamics in ecology has been examined since the 1970s (Forman & Godron, 1986; Risser *et al.*, 1984; Vankat *et al.*, 1991; Wu, 1994; Wu & Levin, 1994; Wu, 1992), although patch dynamics as a conceptual framework has been central to landscape ecology in theory and practice since its emergence. Also, it is likely that managers of dwarf shrub vegetation require information at a patch scale as this is the scale at which they will manage vegetation.

Correlation analysis was used to examine the relationship between explanatory variables and percentage change in area of dwarf shrub vegetation between 1978 and 1987, and 1987 and 1996 (see Chapter 3, Table 3.6). Simple regression analysis provided the patch-based predictive model. Regression is a statistical method commonly used in ecology to explore relations between species and environment (Osborne & Wiley, 1988; Broschart *et al.*, 1989; Johnston *et al.*, 1992; Moore *et al.*, 1993; Abramsky *et al.*, 1996; Sarre *et al.*, 1995; Philippi, 1993; Trexler & Travis, 1993 and Aitkin & Francis, 1982). The initial choice of explanatory variables was, as is usual (Nicholls, 1991), determined by hypotheses about the ecological processes driving a dwarf shrub vegetation system (see Chapter 2.3.1).

Initially, change over time in the areal extent of dwarf shrub vegetation was analysed. Any increases in area of dwarf shrub vegetation were, in all likelihood, the result of management (dwarf shrub vegetation will, in the absence of management or disturbance, undergo succession to scrub and woodland) and decreases were most likely due to natural ecological succession (for the same reason) or due to changes in land use. Given this rationale, only those patches which either did not change or decreased in area of dwarf shrub vegetation over time were included in the modelling process. Thus, the small number of patches which increased in area of dwarf shrub vegetation were removed. The increases in area of dwarf shrub vegetation (managed change) are investigated in Chapter 6. In total, 116 patches were created in the GIS using a simple nearest neighbour rule of eight (see Chapter 3.3.2).

4.3 Areal change

Areal change on a patch-basis was examined in the aggregated primary categories and the primary categories to indicate whether the areal extent of dwarf shrub vegetation in Dorset was changing overall.

4.3.1 Areal change, 1978-1987

Initially, change was examined at the aggregated primary category level followed by the primary category level.

4.3.1.1 Areal change in aggregated primary categories, 1978-1987

Areal change (change in the areal extent of each category in km^2) and percentage change (change in the area of each category as a percentage of the initial area) between 1978 and 1987 were calculated for each aggregated primary category on a patch basis (Table 4.1). It appeared that the losses in area of dwarf shrub vegetation were mostly the result of changes in land use ('others' see Chapter 3, 3.2.3 for a definition), rather than succession. However, as the data were not spatially explicit the exact cause or causes of the decline in area of dwarf shrub vegetation was not clear. There was an increase in area of invasive species suggesting that some succession was occurring, but the increase was not substantial. Overall, there was a clear trend towards a loss in area of dwarf shrub vegetation over time. Indeed, the rate of loss of dwarf shrub vegetation was 1% per annum.

Table 4.1. Areal and percentage change in aggregated primary categories, 1978-1987

Aggregated primary	**Total area, 1978 (km^2)**	**Total area, 1987 (km^2)**	**Areal change, 1978-1987(km^2)**	**Percentage change, 1978-1987(%)**
Total dwarf shrub vegetation	5,510	4,978	- 532	- 10
Invasive species	3,044	3,163	119	4
'Others'	3,745	4,162	417	11

4.3.1.2 Areal change in primary categories, 1978-1987

Areal change and percentage change between 1978 and 1987 were estimated for each primary category (see Chapter 3.2.3 for a definition of the primary categories) on a patch basis (Table 4.2). Examining the areal change in the primary categories further indicated the causes behind the 532 km^2 loss in area of dwarf shrub vegetation over the nine years.

Table 4.2. Areal and percentage change in primary categories between 1978-1987

Primary categories	**Total area, 1978 (km^2)**	**Total area, 1987 (km^2)**	**Areal change, 1978-1987 (km^2)**	**Percentage change, 1978-1987 (%)**
Dry heath	2,587	1,992	- 595	- 23
Wet heath	852	811	- 41	- 5
Humid heath	1,479	1,589	110	7
Peatland	591	585	- 6	- 1
Woodland	1,848	1,890	42	2
Scrub	1,001	1,073	72	7
Carr	194	198	4	2
Grass	1,072	1,416	344	32
Agriculture	612	750	138	23
Horticulture	9	6	- 3	- 28
Farm buildings	8	13	5	63
Industrial buildings	57	58	1	2
Other buildings	31	56	25	81
Houses and gardens	424	568	144	34
Bare ground	1,057	797	- 260	- 25
Hedges and boundaries	31	51	20	63
Sand dunes	18	14	- 4	- 21
Open water	369	386	17	4
Brackish marsh	51	41	- 10	- 19

The area of dry heath decreased by 595 km^2 (23%) in nine years. However, the area of humid heath increased by 110 km^2 (7%). The area of scrub increased by 72 km^2 (7%) in the same time. Other noteworthy changes included an increase in area of grassland of 344 km^2, an increase in the area of agriculture of 154 km^2 and an increase in the area of houses and gardens of 144 km^2. Also, the area of bare ground decreased by 260 km^2. Although the data were not spatially explicit, there appears to be a general trend of change from dwarf shrub vegetation species to either grassland, agriculture or houses and gardens. Scrub, carr and woodland increased relatively little suggesting that little succession occurred. Although the different dwarf shrub vegetation types (dry, wet, humid heath and peatland) changed in different ways, the overall trend appeared to be towards a loss in area of 'heath' and changes in land use appeared to be the most likely cause of such a trend.

4.3.2 Areal change, 1987-1996

Areal change and percentage change between 1987 and 1996 were estimated for each aggregated primary category on a patch basis. The analysis was repeated at the primary category level.

4.3.2.1 Areal change in aggregated primary categories, 1987-1996

Areal change between 1987 and 1996 was estimated (Table 4.3). Over the nine year period the area of invasive species increased by 1,454 km^2 (46%) and the total area of dwarf shrub vegetation decreased by 756 km^2 (15%). Most interesting is the reversal in the trend seen in 1978 towards an increase in 'others'. Between 1978 and 1987 the area of 'others' increased by 417 km^2, however, between 1987 and 1996 the area of 'others' decreased by 698 km^2. The trend towards loss in area of dwarf shrub vegetation not only appeared to continue, but, the rate of change appeared to accelerate increasing from 1% between 1978 and 1987 to 2% between 1987 and 1996. Succession appeared to have replaced land use change as the major cause of change in area of dwarf shrub vegetation.

Table 4.3. Percentage change in aggregated primary categories between 1987-1996

Aggregated primary	Total area, 1987 (km)	Total area, 1996 (km)	Areal change, 1987-1996 (km^2)	Percentage change, 1987-1996 (%)
Total dwarf shrub vegetation	4,978	4,222	- 756	- 15
Invasive species	3,163	4,617	1,454	46
'Others'	4,162	3,464	- 698	- 17

4.3.2.2 Areal change in primary categories, 1987-1996

Examining areal change in the primary categories provided greater information on the patterns of change identified at the aggregated primary category level (Table 4.4). The area of dry heath decreased by only 0.92 km^2 (4%) over the nine year period in comparison to a 595 km^2 (23%) decrease between 1978 and 1987. The area of wet heath decreased considerably (- 466 km^2) although between 1978 and 1987 it decreased by only 41 km^2. The area of peatland also decreased (- 179 km^2) over the nine year period in contrast with a decrease of only 6 km^2 over the previous nine years. The area of humid heath also decreased but to a lesser degree (- 25 km^2). However, woodland (1011 km^2) and scrub (367 km^2) increased considerably over the nine year period. Succession from dwarf shrub vegetative species to scrub species appeared to have occurred and was the most likely cause of the losses in area of dwarf shrub vegetation.

Table 4.4. Percentage change in primary categories between 1987-1996

Primary categories	**Total area, 1987 (km^2)**	**Total area, 1996 (km^2)**	**Areal change, 1987-1996 (km^2)**	**Percentage change, 1987-1996 (%)**
Dry heath	1,997	1,905	- 92	- 4
Wet heath	811	345	- 466	- 57
Humid heath	1,589	1,564	- 25	- 2
Peatland	585	406	- 179	- 30
Woodland	1,890	2,901	1011	53
Scrub	1,073	1,440	367	34
Carr	198	148	- 50	- 49
Grass	1,416	1,748	332	23
Agriculture	750	377	- 373	- 50
Horticulture	6	9	3	31
Farm buildings	13	15	2	16
Industrial buildings	58	42	- 16	- 27
Other buildings	56	62	6	11
Houses and gardens	568	331	- 237	- 42
Bare ground	797	333	- 464	- 58
Hedges & boundaries	51	121	70	136
Sand dunes	14	11	- 3	- 24
Open water	386	254	- 132	- 34
Brackish marsh	41	30	- 11	- 27

4.3.2.3 Overall areal change, 1978-1996

Between the first and last surveys several distinct patterns of change emerged. The area of dwarf shrub vegetation decreased as the area of 'others' and the area of invasive species increased. However, between 1978 and 1987 change in area of dwarf shrub vegetation as a whole most probably resulted from increased urbanisation, agriculture and to a lesser degree, invasive species. The influence of changes in land use on change in area of heath lessened between 1987 and 1996 as a result of Government planning policies and environmental legislation. However, there were large increases in the area of invasive species. Grassland continued to increase in area although housing decreased as did agriculture. Thus, the likely processes behind the decreases in dwarf shrub vegetation varied over time as did the rates of change.

4.4 Summarising the data distributions

Histograms for each aggregated primary category explanatory variable in 1978, 1987 and 1996 were plotted to describe the distribution of each variable. Several of these are shown in this section. By comparing histograms of the same variable but for different years, changes in the dispersion of data can be examined. Histograms for the primary categories are not given

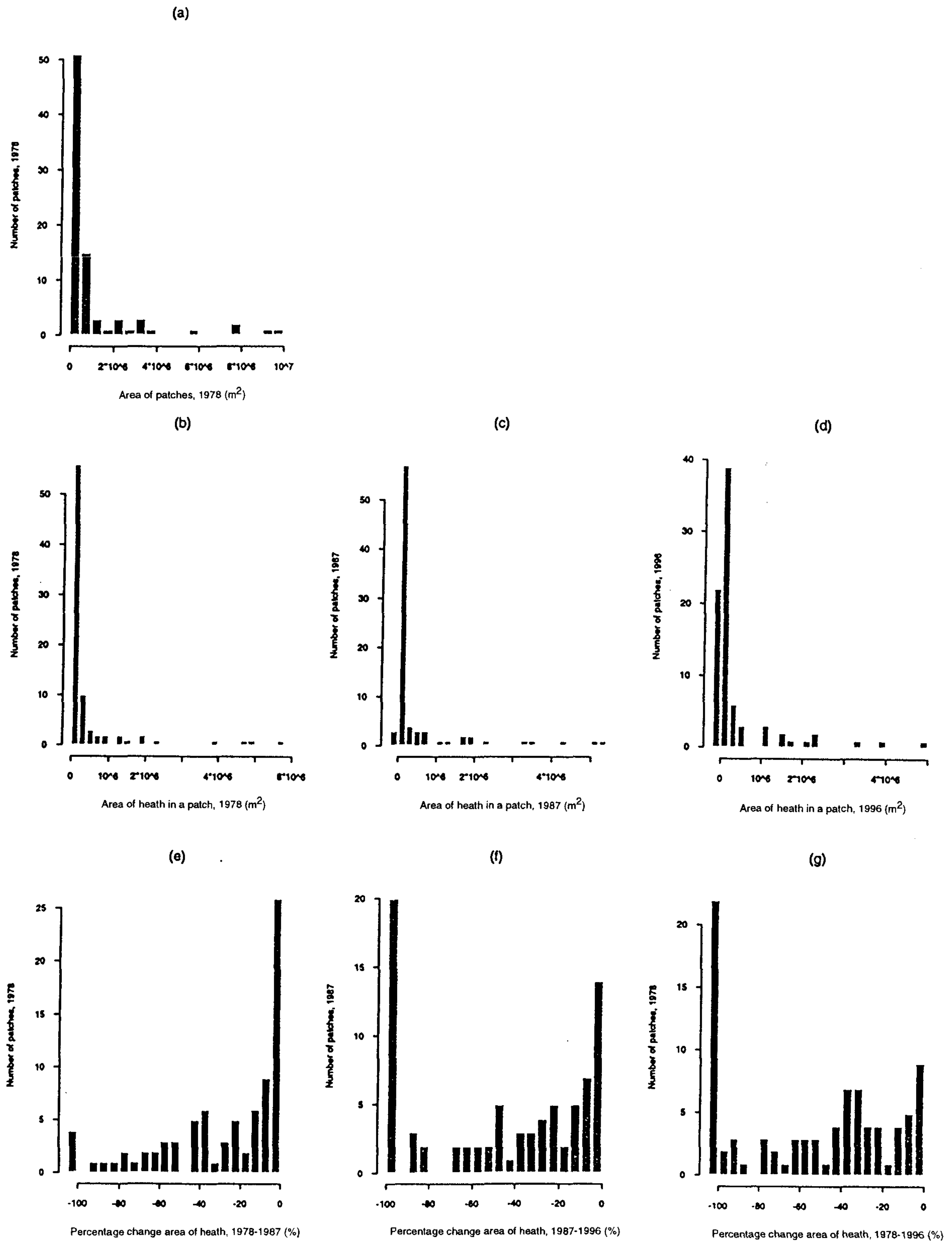


Fig. 4.1 Histograms of (a) area of patches, 1978 (m^2); (b) area of dwarf shrub vegetation in a patch, 1978 (m^2); (c) area of dwarf shrub vegetation in a patch, 1987 (m^2); (d) area of dwarf shrub vegetation in a patch, 1996 (m^2); (e) percentage change in area of dwarf shrub vegetation, 1978-1987 (%); (f) percentage change in area of dwarf shrub vegetation, 1987-1996 (%); (g) percentage change in area of heath, 1978-1996 (%).

as the results were similar to those for the aggregated primary categories. This similarity is unsurprising because the aggregated primary categories, as outlined previously, were derived by amalgamating the primary categories. Only patches in which the area of dwarf shrub vegetation declined as a percentage of initial area were plotted.

4.4.1 Histograms of aggregated primary categories, 1978, 1987 and 1996

The majority of patches of dwarf shrub vegetation in 1978 were small, with only a small number of larger patches. Indeed most of the patches covered an area of only 40,000 m^2 (a single pixel) (Fig. 4.1a). The largest patch extended over 9,640,000 m^2 and the median patch size was 240,000 m^2.

The histogram of the area of dwarf shrub vegetation in a patch in 1978 (Fig. 4.1b) reflected the pattern in Figure 4.1a because patches were created based on whether or not a pixel contained dwarf shrub vegetation. That is, there is an approximately linear relation between patch size and the area of dwarf shrub vegetation in a patch ($r^2 = 0.91$). There was little change in this distribution in 1987 (Fig. 4.1c) and 1996 (Fig. 4.1d). However, the number of patches containing a very small area of dwarf shrub vegetation increased. All three plots appear to indicate that the dwarf shrub vegetation of Dorset is concentrated in a large number of very small patches, with the remaining heathland spread across patches of varying sizes.

Most patches decreased in area of dwarf shrub vegetation between 1978 and 1987 (Fig. 4.1e), with fewer experiencing a large negative percentage change. In all, the area of heath increased in thirty three patches, decreased in sixty six and remained unchanged in seventeen. Percentage change in area of dwarf shrub vegetation between 1987 and 1996 was plotted (Fig. 4.1f). The area of dwarf shrub vegetation increased in thirty four patches, decreased in seventy four and remained unchanged in eight. Small decreases in area of dwarf shrub vegetation dominated the majority of patches. Larger percentage decreases occurred in a few patches but, in contrast to Figure 4.1e, a large number of patches decreased in area of dwarf shrub vegetation by 100%, that is, they disappeared. This difference (few patches between 1978 and 1987 decreasing to zero) will be revisited in Chapter 5, where it has consequences for the analysis. Overall, between 1978 and 1996 most patches experienced a large negative percentage change in area of dwarf shrub vegetation (Fig. 4.1g) reflecting the frequency distribution for percentage change between 1987 and 1996 (Fig. 4.1f).

4.5 Feature space plots

The analysis of areal change described overall change in the dwarf shrub vegetation of Dorset. It was clear from the analysis that the area of dwarf shrub vegetation was in decline. Two processes appeared to account for the decline in dwarf shrub vegetation. However, it was not possible to conclude that the decline in dwarf shrub vegetation was a direct consequence of changes in land use and of succession. An alternative analysis was carried out to gain further insight into the spatial dynamics of the area of dwarf shrub vegetation, the area of invasive species and the area of 'others' in a patch. Feature space plots of percentage change in each of the aggregated primary categories were plotted to indicate what the area of dwarf shrub vegetation was being replaced by.

Percentage change between 1978 and 1987 was examined initially. Percentage change in area of invasive species was plotted against percentage change in area of dwarf shrub vegetation (Fig. 4.2a). The area of dwarf shrub vegetation in the majority of patches declined, and in many patches the declining dwarf shrub vegetation appeared to be replaced by invasive species. When percentage change in area of 'others' was plotted against percentage change in area of invasive species (Fig. 4.2b) the area of invasive species did not cause change in the area of 'others' and *vice versa*. Finally, percentage change in area of 'others' was plotted against percentage change in area of dwarf shrub vegetation (Fig. 4.2c). Again, the area of dwarf shrub vegetation decreased in the majority of patches. However, the area of 'others' appeared to account for much of this change.

Next, percentage change between 1987 and 1996 was examined. Percentage change in area of invasive species was plotted against percentage change in area of dwarf shrub vegetation (Fig. 4.2d). The decline in area of dwarf shrub vegetation in several patches was related to increases in invasive species. When percentage change in area of 'others' was plotted against percentage change in area of invasive species (Fig. 4.2e), the area of invasive species appeared to be responsible for a considerable amount of change in the area of 'others'. In particular, the area of agriculture and bare ground fell, and the area of woodland increased, which may account for this relationship. Finally, percentage change in area of dwarf shrub vegetation was plotted against percentage change in area of 'others' (Fig. 4.2f). The area of 'others' accounted for change in area of dwarf shrub vegetation. However, change in land use ('others') caused fewer changes in area of dwarf shrub vegetation than between 1978 and 1987.

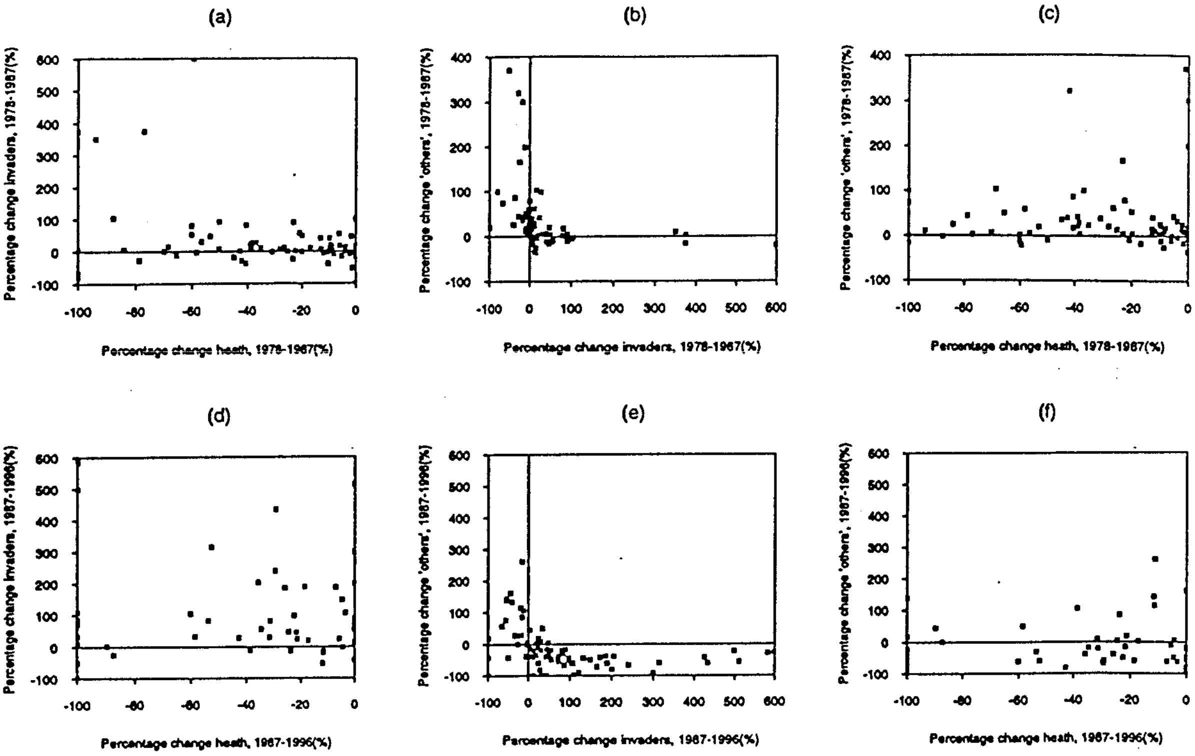


Fig. 4.2 Feature space plots of (a and d) percentage change in area invasive species against percentage change in area of dwarf shrub vegetation; (b and e) percentage change in area of 'others' against percentage change in area if invasive species; (c and f) percentage change in area of 'others' against percentage change in area of dwarf shrub vegetation.

4.6 Mapping change

It was clear from the analysis of areal change over time (Chapter 4, 4.3) and from the histograms (Chapter 4, 4.4) that change was occurring. However, to aid the *explanation* of change, the data were considered in a spatial context. The heathlands of Dorset have been mapped at many points in time (Isaac Taylor, 1759 & 1756; Moore, 1962 and Webb & Haskins, 1980) to illustrate heathland fragmentation. The spatial element is important. It is not enough to know that a patch is changing at a particular rate. It is also important to know which patches are changing, especially as patches are not isolated. Change must be examined as part of a functioning landscape.

4.6.1 Mapping change between 1978 and 1987

Percentage change in area of dwarf shrub vegetation between 1978 and 1987 was mapped on a patch basis (Fig. 4.3). The area of dwarf shrub vegetation in the majority of patches decreased between 1978 and 1987. However, change was not uniform across all patches. There appeared to be no structure to the change.

To increase the contrast in the maps, different thresholds of change were used to define changes. 'No change' represented less than or equal to a 10% decrease, or increase, in area of dwarf shrub vegetation. 'Decreased heath' represented a loss of dwarf shrub vegetation of greater than -10% and 'increased heath' represented an increase in the area of dwarf shrub vegetation of greater than +10%. The data were re-mapped accordingly (Fig. 4.4). The result was similar to the original map of change (Fig. 4.3). Again, the overall pattern of change appears to be that of a decrease in area of dwarf shrub vegetation in a patch over time, but change was not uniform across all patches.

4.6.2 Mapping change between 1987 and 1996

Percentage change in area of dwarf shrub vegetation between 1987 and 1996 was mapped on a patch basis (Fig. 4.5). There appeared to be little structure to the change. However, the area of dwarf shrub vegetation declined in most patches. The alternative mapping thresholds described in section 4.5.1 of this chapter were applied and percentage change remapped (Fig. 4.6). Overall, the picture remained the same.

4.6.3 Mapping percentage change in the remaining aggregated primary categories

Percentage change in area of invasive species was mapped (Fig 4.7). Again, there was no apparent structure to the change even though the area of invasive species increased in many patches. The map of change between 1987 and 1996 (Fig. 4.8) was similar. Change was not uniform across all Dorset, but the area of invasive species increased in many patches.

Percentage change in area of 'others' between 1978 and 1987 was mapped (Fig. 4.9) and was similar to that for area of invasive species. The area of 'others' increased in many patches but there was no structure to the change. Percentage change in 'others' between 1987 and 1996 (Fig. 4.10) was similar.

4.6.4 Mapping percentage change in selected primary categories

The primary categories which underwent the greatest areal changes over time between 1978 and 1987, and 1987 and 1996 were mapped (Figs. 4.11-4.16). A positive percentage change in grassland between 1978 and 1987 (Fig. 4.11) occurred over most patches, but as before, change was not uniform. When percentage change in grassland between 1987 and 1996 was mapped (Fig. 4.12) the result was very similar.

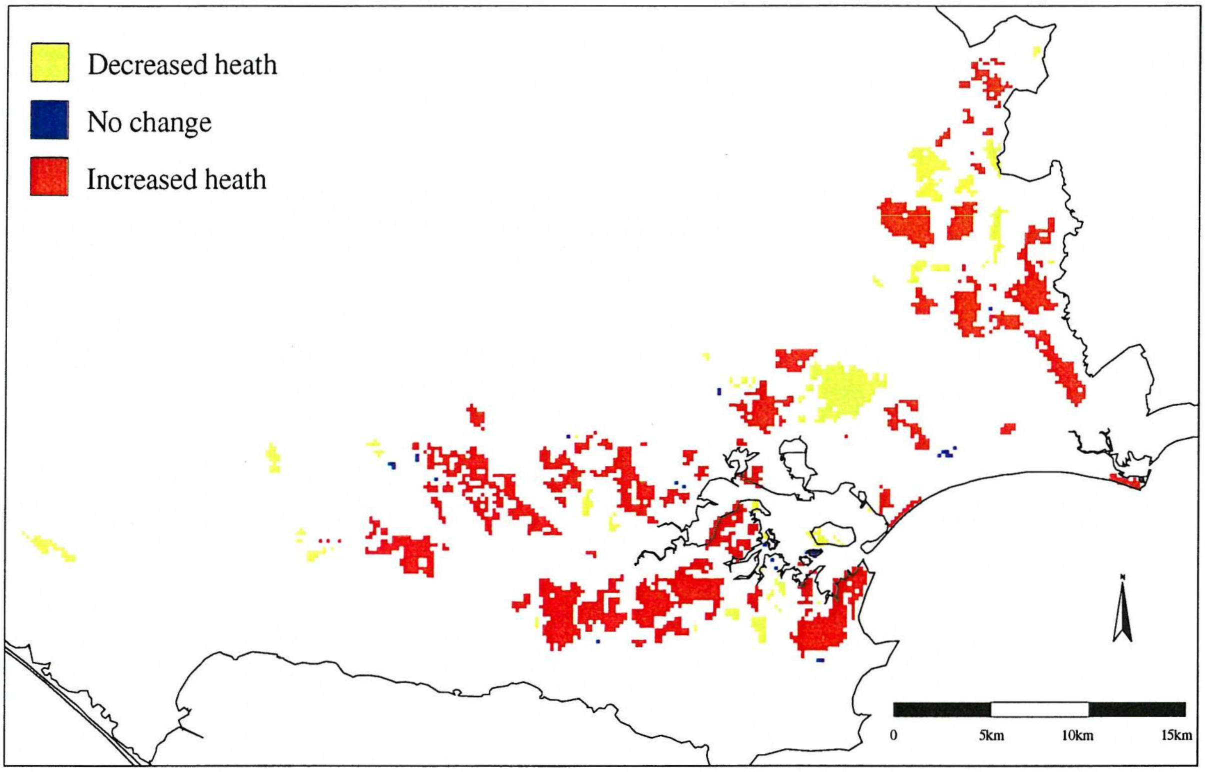


Fig. 4.3 Percentage change in area of heath in a patch, 1978 –1987

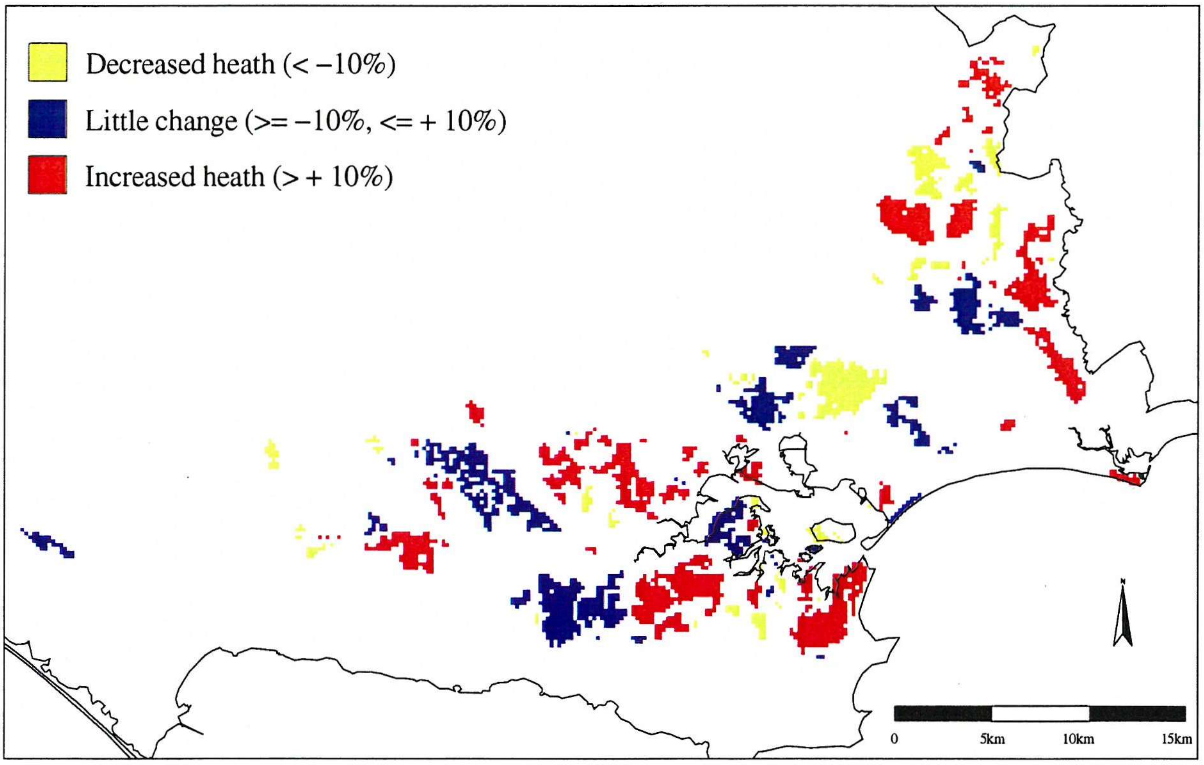


Fig. 4.4 Percentage change in area of heath in a patch, 1978 –1987

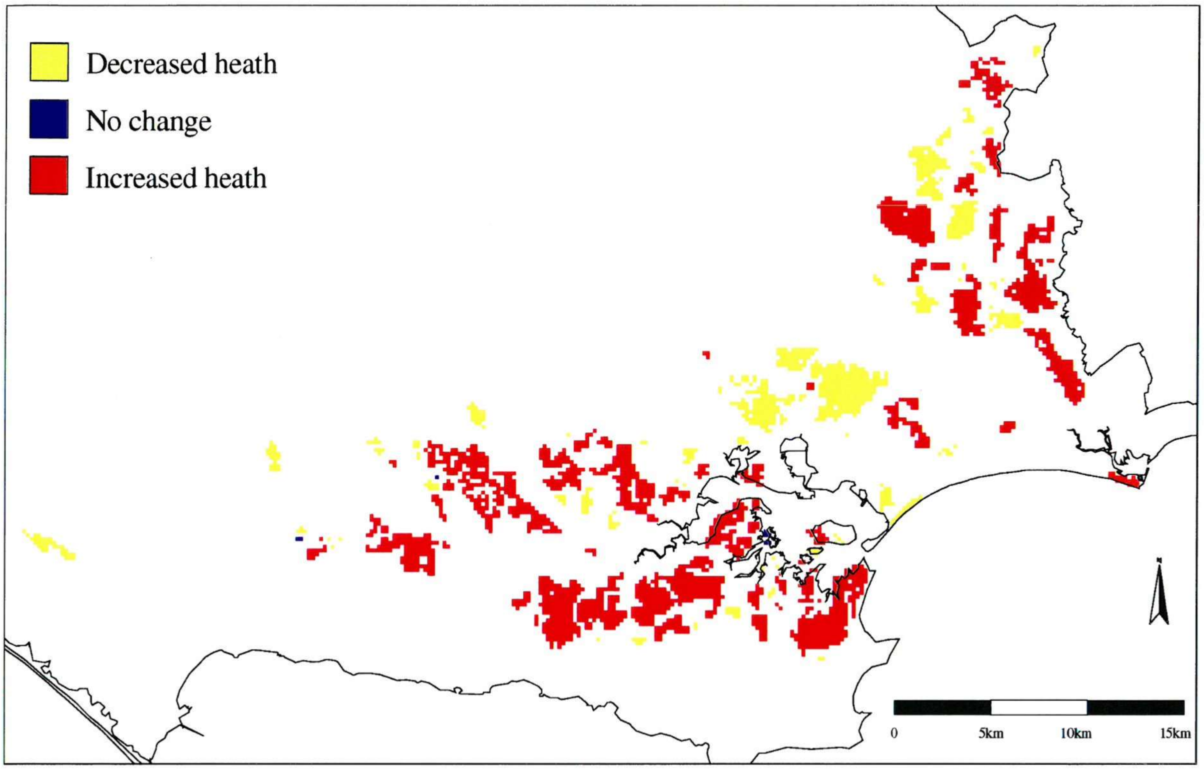


Fig. 4.5 Percentage change in area of heath in a patch, 1987 –1996

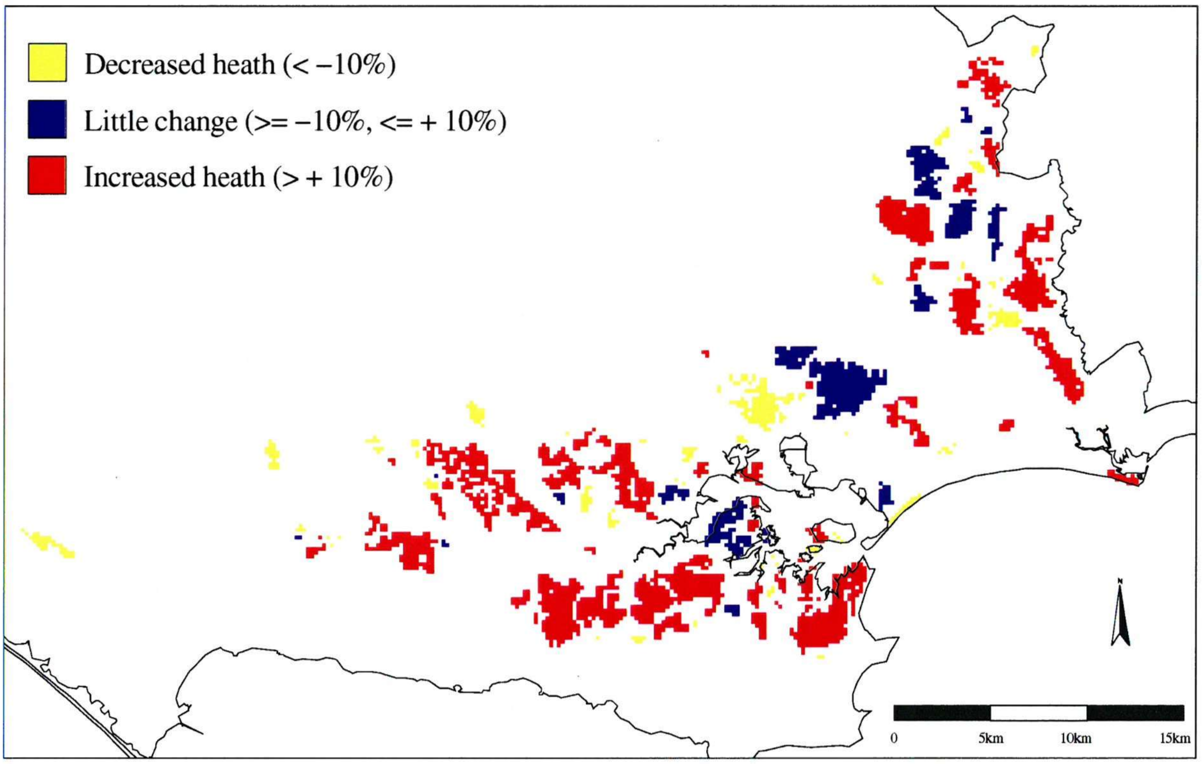


Fig. 4.6 Percentage change in area of heath in a patch, 1987 –1996

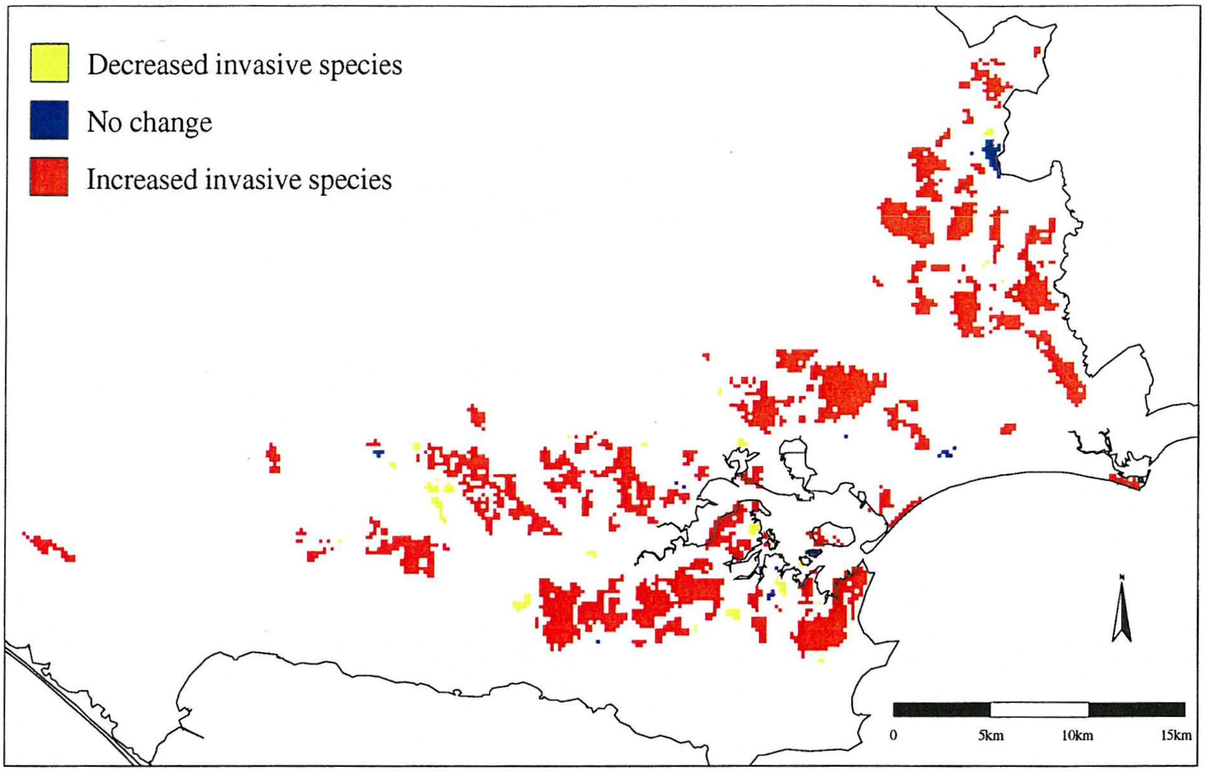


Fig. 4.7 Percentage change in area of invasive species in a patch, 1978 –1987

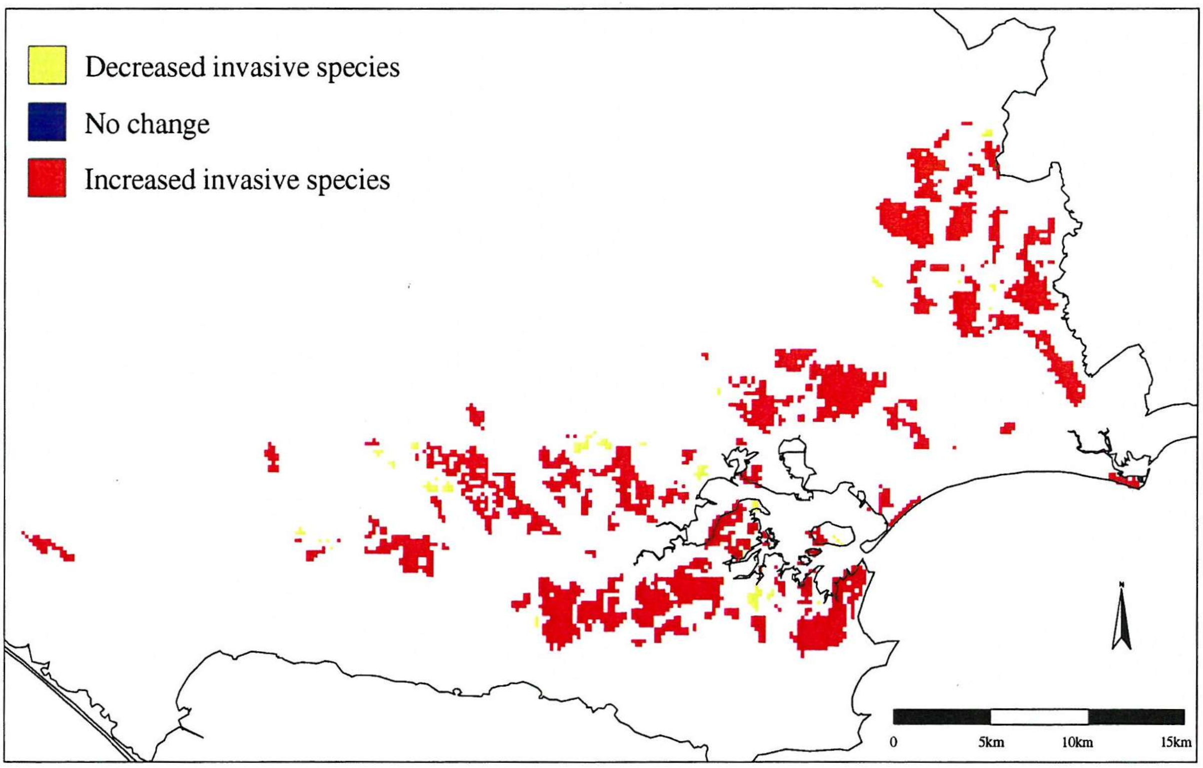


Fig. 4.8 Percentage change in area of invasive species in a patch, 1987 –1996

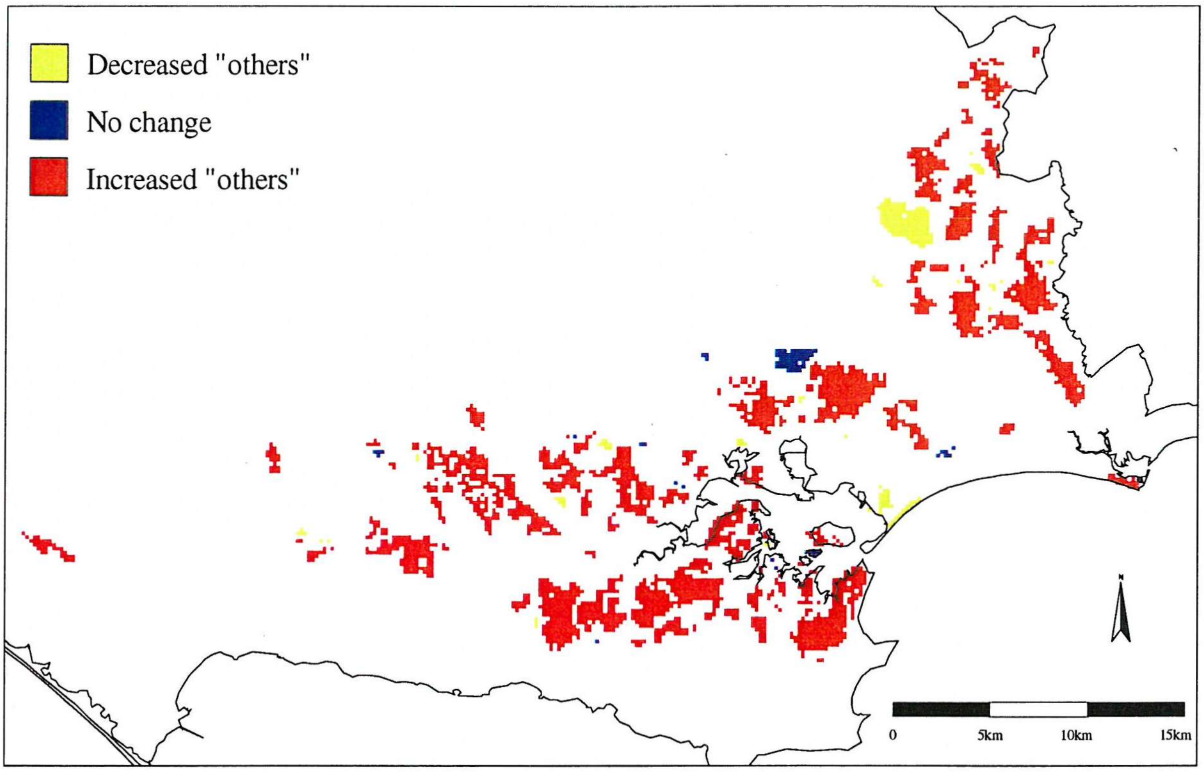


Fig. 4.9 Percentage change in area of "others" in a patch, 1978 –1987

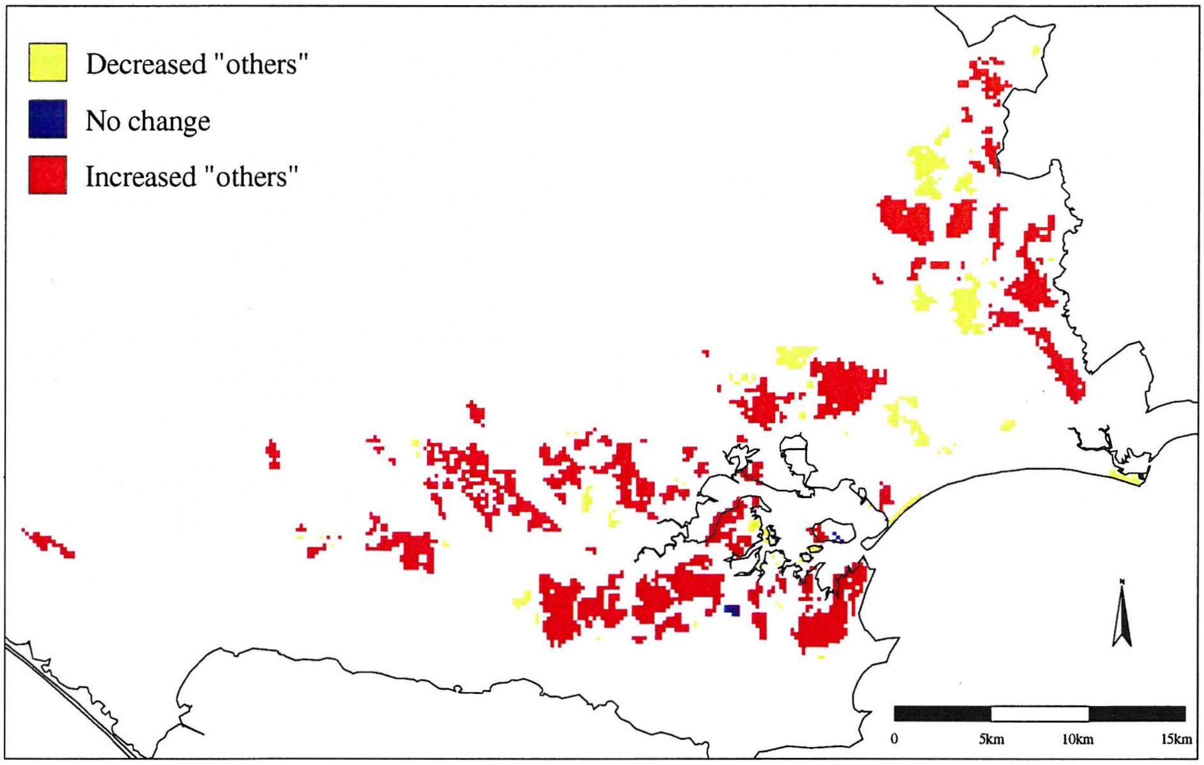


Fig. 4.10 Percentage change in area of "others" in a patch, 1987 –1996

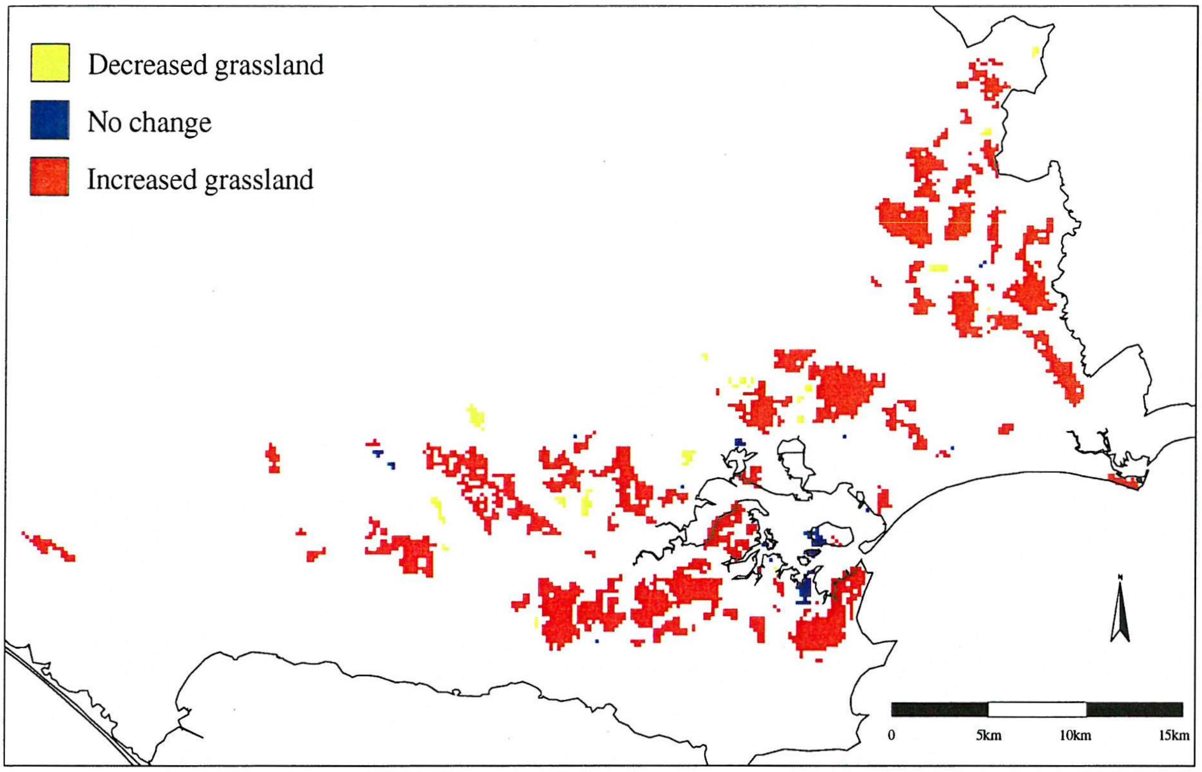


Fig. 4.11 Percentage change in area of grassland in a patch, 1978 –1987

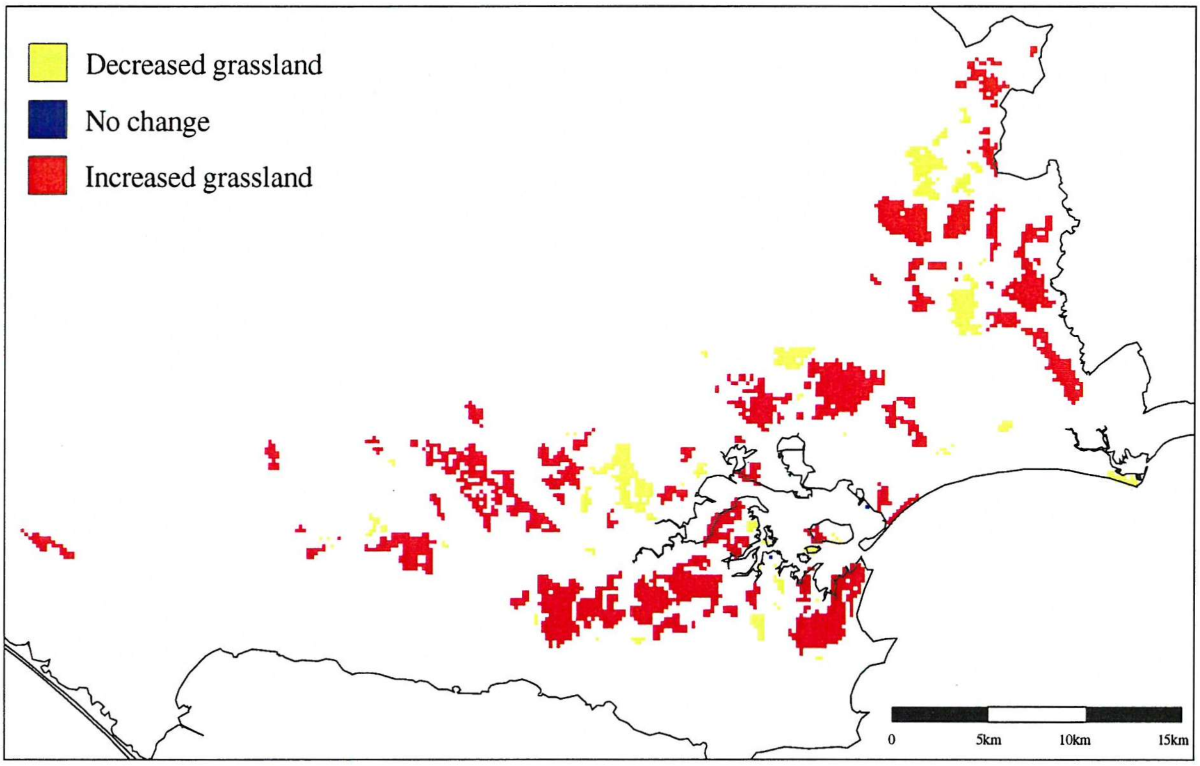


Fig. 4.12 Percentage change in area of grassland in a patch, 1987 –1996

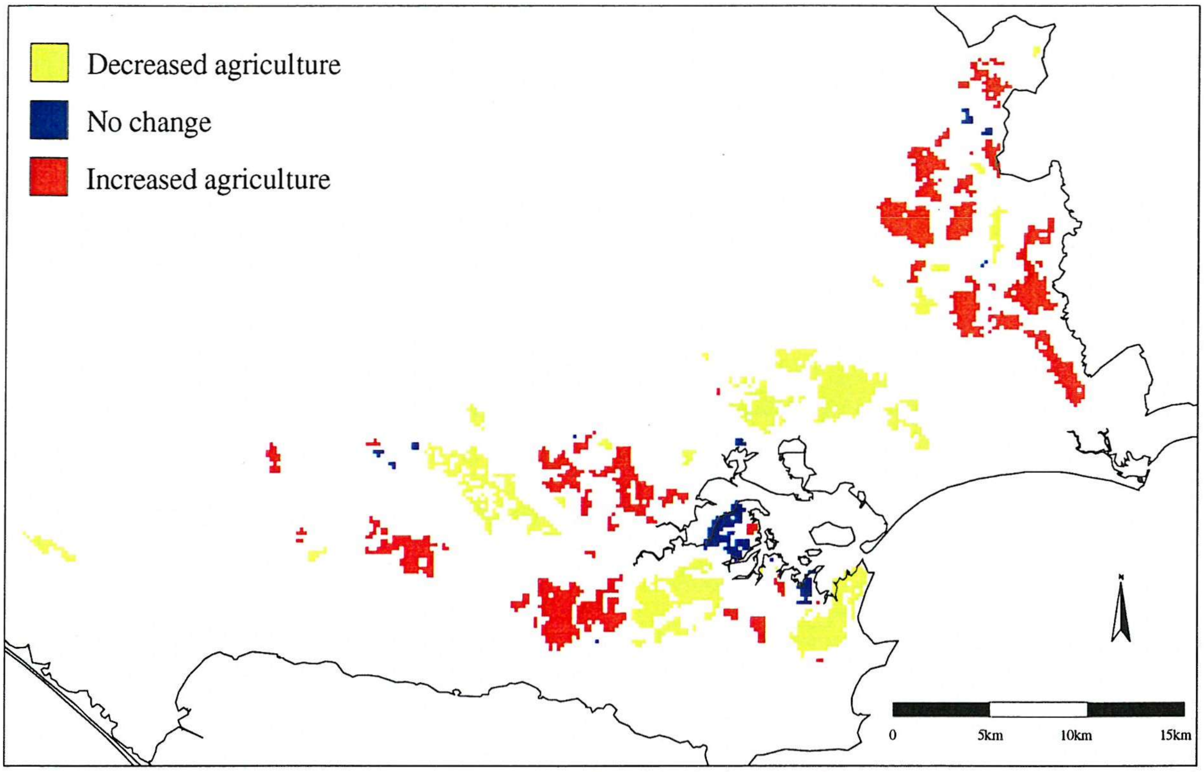


Fig. 4.13 Percentage change in area of agriculture in a patch, 1978 –1987

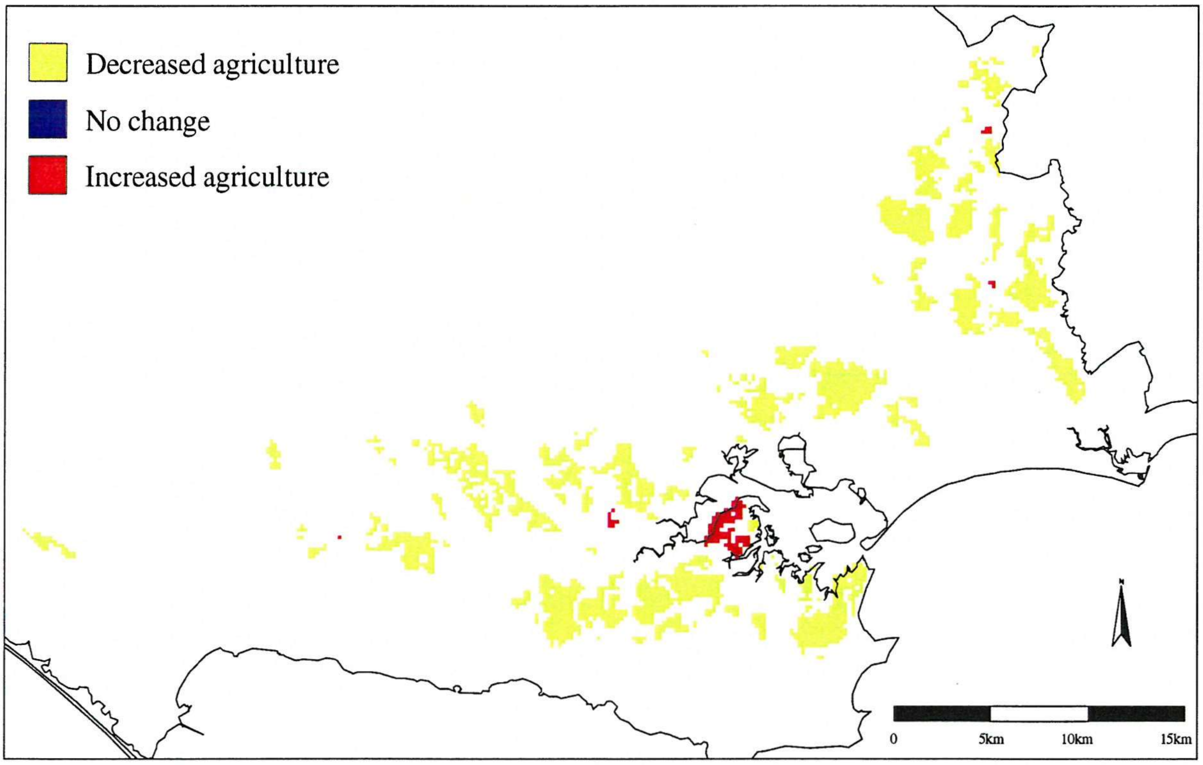


Fig. 4.14 Percentage change in area of agriculture in a patch, 1987 –1996

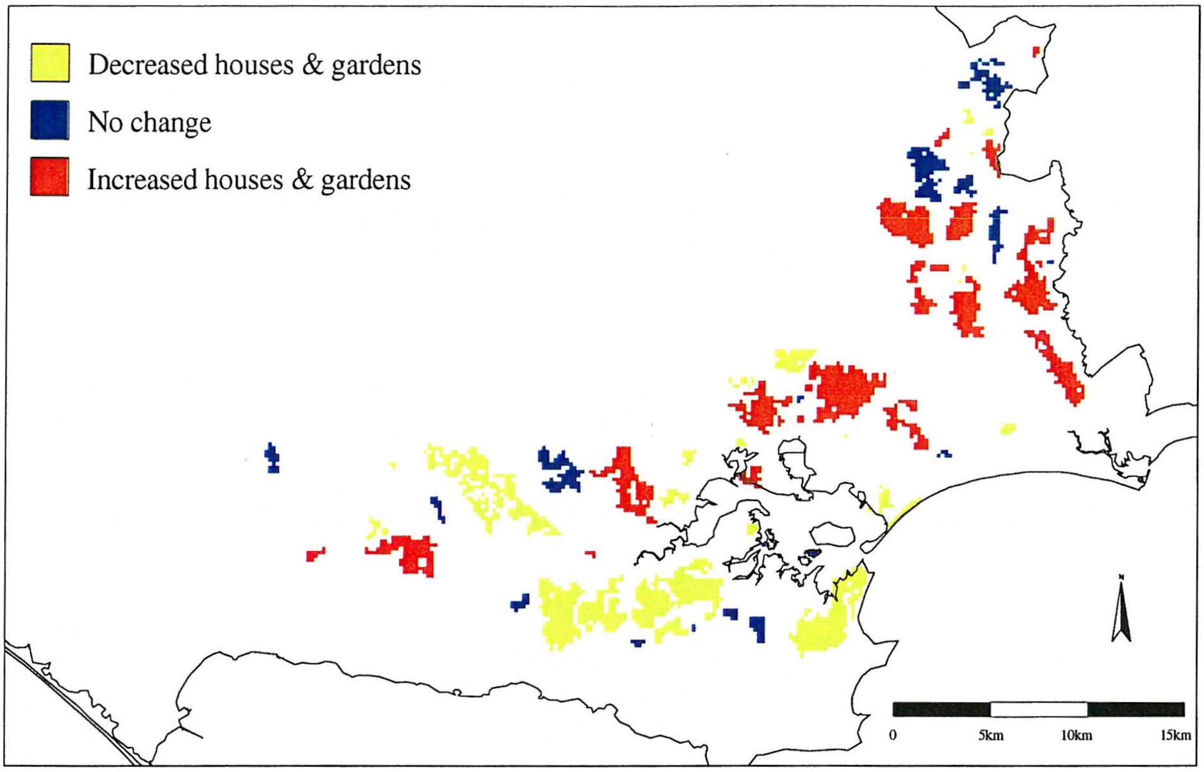


Fig. 4.15 Percentage change in area of houses and gardens in a patch, 1978 –1987

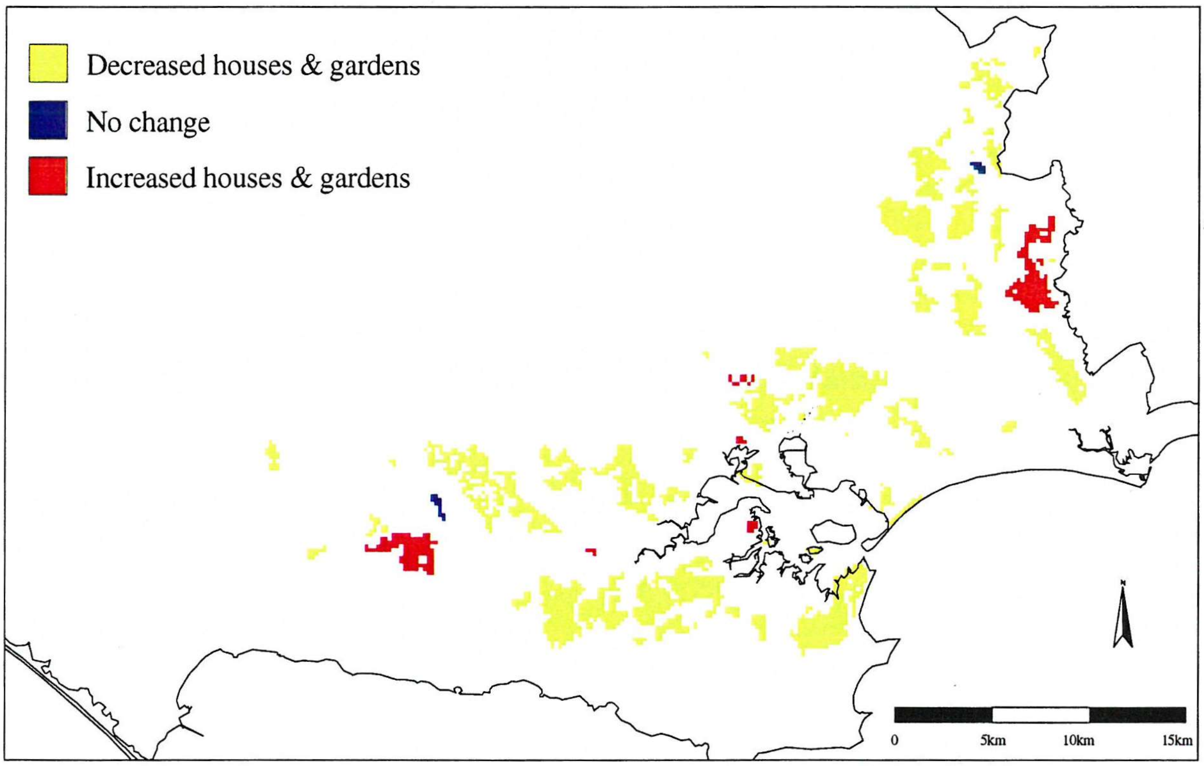


Fig. 4.16 Percentage change in area of houses and gardens in a patch, 1987 –1996

Percentage change in agriculture between 1978 and 1987 was mapped (Fig. 4.13). Again there was no apparent structure to the change. When percentage change in area of agriculture between 1987 and 1996 was mapped (Fig. 4. 14) the area of agriculture declined in many patches. Despite this, percentage change was not uniform across all Dorset.

Finally, percentage change in area of houses and gardens between 1978 and 1987 was mapped (Fig. 4.15). Although the area of houses and gardens remained unchanged in many patches, there was no structure to the change. Percentage change between 1987 and 1996 was similar (Fig. 4.16). However, it had not been expected that the area of houses and gardens could decline. This aside, change in area of houses and gardens across all Dorset was not uniform.

Overall, no distinct spatial pattern was discernible from the maps produced, although there was an obvious temporal trend towards a decrease in area of dwarf shrub vegetation, an increase in invasive species and the area of 'others' increased initially before decreasing.

4.7 Bivariate and multivariate analysis of change on a patch-basis

To examine the trends and patterns of change in the dwarf shrub vegetation of Dorset quantitatively, both correlation and simple regression were used. It was anticipated that such analyses would indicate which explanatory variables best accounted for percentage change in area of dwarf shrub vegetation over time.

Multiple regression is an extension of simple regression to take into account the effect of more than one independent variable (X) on the dependent variable (Y) (see Chapter 2, 2.4.3.3). Further, multiple regression allows for correlations between explanatory variables. Multiple regression should, in theory, improve the predictive power of the models.

4.7.1 General introduction to regression analysis

Correlation analysis was carried out to examine the relationship between percentage change and each explanatory variable. Simple regression was then used to test several hypotheses to further account for percentage change in area of dwarf shrub vegetation between 1978 and 1987. The process was repeated for the 1987 and 1996 data. The residuals were examined to ensure that their distribution was approximately normal (see Appendix 3). The initial choice of explanatory variables was determined by considering the ecological processes underlying the system to be modelled (see Nicholls, 1991; Chapter 2, 2.4.3). The explanatory variables chosen for model building were based upon current understanding of patch-based ecological processes in dwarf shrub vegetation (Chapter 3, Table 3.6). The response variable was defined as percentage change in area of dwarf shrub vegetation (Chapter 3, 3.5.1).

If the area of dwarf shrub vegetation (or dwarf shrub vegetation type) in a patch was zero, the patch was removed from the analysis. If such patches had not been removed, percentage change in area of dwarf shrub vegetation would have been zero in several patches because the patches did not contain any area of dwarf shrub vegetation (or dwarf shrub vegetation type) rather than because the area dwarf shrub vegetation (or dwarf shrub vegetation type) remained unchanged. As patches in which the area of dwarf shrub vegetation (or dwarf shrub vegetation type) either remained unchanged or decreased were being analysed, such data were biased.

It was necessary to ensure approximately linear bivariate relations between percentage change and each of the explanatory variables. To examine the linearity of the relationship between percentage change in area of dwarf shrub vegetation between 1978 and 1987 (the response variable) and the explanatory variables, the appropriate scatterplots were examined. For example, percentage change in area of dwarf shrub vegetation between 1978 and 1987 was plotted against the area of dwarf shrub vegetation in a patch (Fig. 4.17). The relationship appeared to be curvilinear rather than linear. It was necessary to transform each explanatory

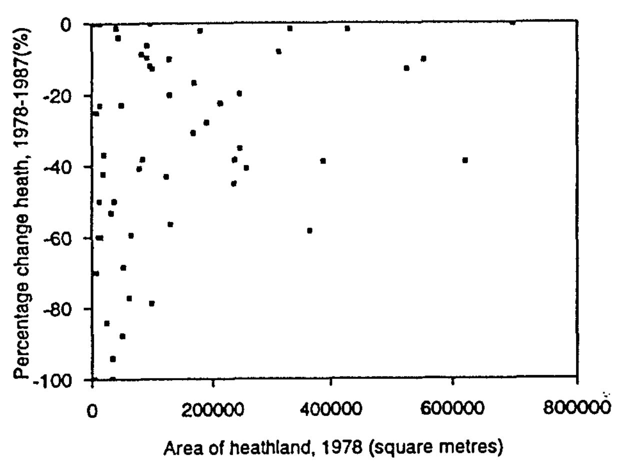


Fig. 4.17 Scatterplot of percentage change in area of dwarf shrub vegetation, 1978-1987 (%) against the area of dwarf shrub vegetation in a patch.

variable and the target variable to ensure that each relationship could be approximated with a linear model. Several transformations were attempted (Table 4.5) (see Chapter 2, 2.4.3.2). The relation which was most linear resulted when the natural logarithm of both axes was used. Since patches with zero percentage change in dwarf shrub vegetation were included in the analysis a value of one was added to the target and explanatory variables prior to logging.

Logistic regression was not used as the data were made linear using a simple logarithmic transformation which made the interpretation of results more straight forward.

Table 4.5. Transformations carried out to ensure an approximately linear relation.

X
Log X
Arcsine X
X^2
$\sqrt{X}$
$\overline{X}$

4.7.2 Regression for the aggregated primary categories, 1978-1987

Correlation analysis and simple regression were carried out to examine the degree to which variation in percentage change in area of dwarf shrub vegetation could be accounted for by each explanatory variable (Chapter 3, Table 3.6; Table 3.7 & Table 3.8). A confidence interval of 95% was used. Therefore, there was a one in twenty chance of a Type I error, that is, rejecting erroneously the null hypothesis (H_0). Because of the complex nature of the ecological system being modelled if the coefficient of determination exceeded 0.10, the hypothesis was accepted.

4.7.2.1 Simple regression for the aggregated primary categories

Percentage change in area of dwarf shrub vegetation between 1978 and 1987 was significantly correlated with four variables. The largest coefficient of determination resulted between percentage change and density of heath in the edge of a patch ($r^2 = 0.15$) (Table 4.6). Despite the low r^2 the relationship was as hypothesised (H_1): the more dense the area of dwarf shrub vegetation in the edge of a patch, the less susceptible a patch is to loss of heath (Fig. 4.18a). Also, percentage change was similarly positively correlated with the area of heath in the edge of a patch (Fig. 4.18b). The ratio of dwarf shrub vegetation to density of invasive species in a patch (and in the edge of a patch) accounted for between 13% - 14% of the variation in percentage change. The relationships supported the hypotheses laid out in Chapter 3 (3.5.2). The greater the density of dwarf shrub vegetation in a patch (or the edge of a patch), the less susceptible that patch is to change (see Figs. 4.18c-d).

It is pertinent at this point to comment on the unusual shape of the plots outlined above (Figs. 4.18a-c). Certain areas of the plot cannot contain data (as a patch of one pixel can only remain unchanged or decrease by 100% (that is disappear), as increases were not included in this analysis). This accounts for their odd shape. However, the inclusion of zeros (percentage change) counters the effect of null areas of the graphs.

Table 4.6. Simple regression results for percentage change in area of heath versus patch-based aggregated primary categories, 1978. Only significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2	Ho / H_1	Relationship
Density of heath	1, 81	0.00067	0.13	H_1	Positive
Density of heath in edge of a patch	1, 81	0.00026	0.15	H_1	Positive
Ratio of heath to invasive species in the edge	1, 81	0.00046	0.14	H_1	Positive
Ratio of heath to invasive species	1, 81	0.00081	0.13	H_1	Positive

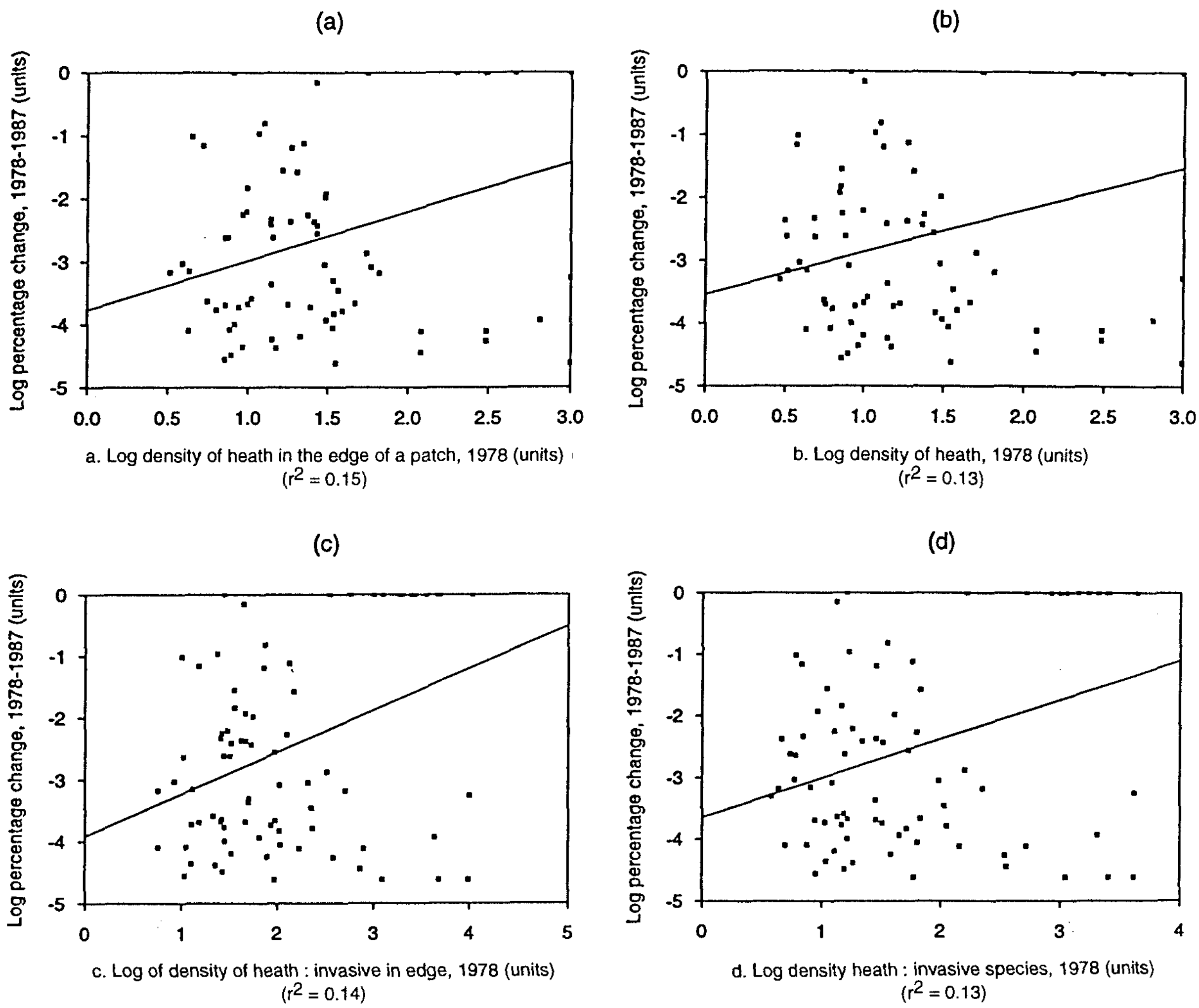


Fig. 4.18 Scatterplots of (a) log percentage change in area of dwarf shrub vegetation, 1978-1987 against log density of dwarf shrub vegetation in the edge of a patch 1978; (b) log percentage change in area of dwarf shrub vegetation, 1978-1987 against log density of dwarf shrub vegetation, 1978; (c) log percentage change in area of dwarf shrub vegetation, 1978-1987 against log ratio of density of dwarf shrub vegetation to invasive species in the edge of a patch, 1978; (d) log percentage change in area of dwarf shrub vegetation, 1978-1987 against log ratio of density of dwarf shrub vegetation to invasive species in a patch, 1978.

4.7.2.2 Multiple regression for the aggregated primary categories, 1978-1987

Percentage change in area of heath between 1978 and 1987 was most highly correlated with the density of dwarf shrub vegetation in the edge of a patch. The log of the ratio of area of dwarf shrub vegetation to 'others' accounted for a significant part of the residuals (Table 4.7). In all, 17% of the variation in percentage change was accounted for. The correlation between percentage change and density of heath in the edge of a patch may indicate that the degree of fragmentation in the edge of a patch influences percentage change. Further, the area of dwarf shrub vegetation relative to the area of 'others' (anthropogenic activity) in a patch influenced percentage change when density of dwarf shrub vegetation in the edge was held constant. The ratio of area of dwarf shrub vegetation to area of 'others' in a patch reflects the degree of fragmentation of the area of dwarf shrub vegetation within a patch. Despite the small coefficient of determination ($r^2 = 0.17$), the multiple regression equation could be considered for use as a predictor of change. The regression equation is as follows:

Log (percentage change) = 4.2 + 1.1 log (density of dwarf shrub vegetation in the edge) + 0.3 log (ratio of area of dwarf shrub vegetation to 'others').

The equation can be used to account for 17% of the variation in percentage change in area of dwarf shrub vegetation between 1978 and 1987. It could be used to predict in the future if it can be assumed that set of the relations modelled by the equation are constant over time.

Table 4.7 Multiple regression for patch-based aggregated primary categories, 1978.

Logged, patch-based explanatory variables	*df*	*p*	r^2
Density of heath in the edge	1, 81	0.0002	0.15
+ Area of heath : 'others'	2, 80	0.0012	0.17

4.7.3 Regression for the primary categories, 1978-1987

At the primary category level, four response variables were utilised: the four primary categories which made up the total 'heathland' category. Therefore, the relationships between percentage change in area of dry, wet, humid heath and peatland and each of the explanatory variables were examined in turn.

4.7.3.1 Simple regression for dry heath, 1978-1987

Percentage change in area of dry heath was most highly correlated with the area of scrub in a patch and also with the area of carr in the edge of a patch (both $r^2 = 0.23$). As the percentage of dry heath lost increased, the area of scrub or the area of carr in the edge of a patch increased (Fig. 4.19a & Fig. 4.19b). Both relationships were as hypothesised. The pressure from succession increased with increasing area of invasive species causing the area of dry heath to decline. Eleven other explanatory variables each accounted for between 12% and 18% of the variation in percentage change (Table 4.8). It was hypothesised that percentage change would decrease as the density of dry heath in the edge of a patch increased. The hypothesis appeared to be supported (Fig. 4.19c). The relationship was similar for the density of dry heath in a patch (Fig. 4.19d). However, percentage change was inversely related to the area of dry heath and the area of dry heath in the edge of a patch (Fig. 4.19e-f). These relationships were not as hypothesised but could have been the result of land use change. Dry heath is more easily built upon or converted to agriculture than the wetter heaths (Bullock & Webb, 1995).

Table 4.8. Simple regression for percentage change in area of dry heath versus the patch-based primary categories, 1978. Only the significant relationships are shown.

Logged, patch-based, explanatory variables	df	p	r^2	Ho / H_1	**Relationship**
Area of carr in the edge of a patch	1, 85	2.01e-06	0.23	H_1	Negative
Area of dry heath	1, 85	0.00025	0.15	Ho	Negative
Area of wet heath	1, 85	0.00122	0.12	-	Negative
Area of humid heath	1, 85	0.00055	0.13	-	Negative
Area of woodland in a patch	1, 85	0.00064	0.13	H_1	Negative
Area of scrub in a patch	1, 85	2.3e-06	0.23	H_1	Negative
Density of dry heath	1, 85	8.08e-05	0.17	H_1	Positive
Area of dry heath in the edge of a patch	1, 85	0.00013	0.16	Ho	Negative
Area of wet heath in the edge of a patch	1, 85	0.00112	0.12	-	Negative
Area of humid heath in the edge of a patch	1, 85	0.00049	0.13	-	Negative
Area of scrub in the edge of a patch	1, 85	0.00063	0.13	H_1	Negative
Density of dry heath in the edge of a patch	1, 85	4.32e-05	0.18	H_1	Positive
Area of dry heath : scrub	1, 85	0.0010	0.12	H_1	Positive

In summary, not all the hypotheses laid out in Chapter 3 (3.5.2) were supported. Further, several significant relationships were unexpected (see Table 4.8). These relationships appeared to indicate that percentage change in area of dry heath is not only affected by succession. Fluctuations in area of dwarf shrub vegetation types also influenced change. For example, a particularly dry summer may cause wetter areas of dwarf shrub vegetation to dry out (N. Webb & R. Rose *pers comm.*). Therefore, the boundaries between the dwarf shrub vegetation types are in continual flux.

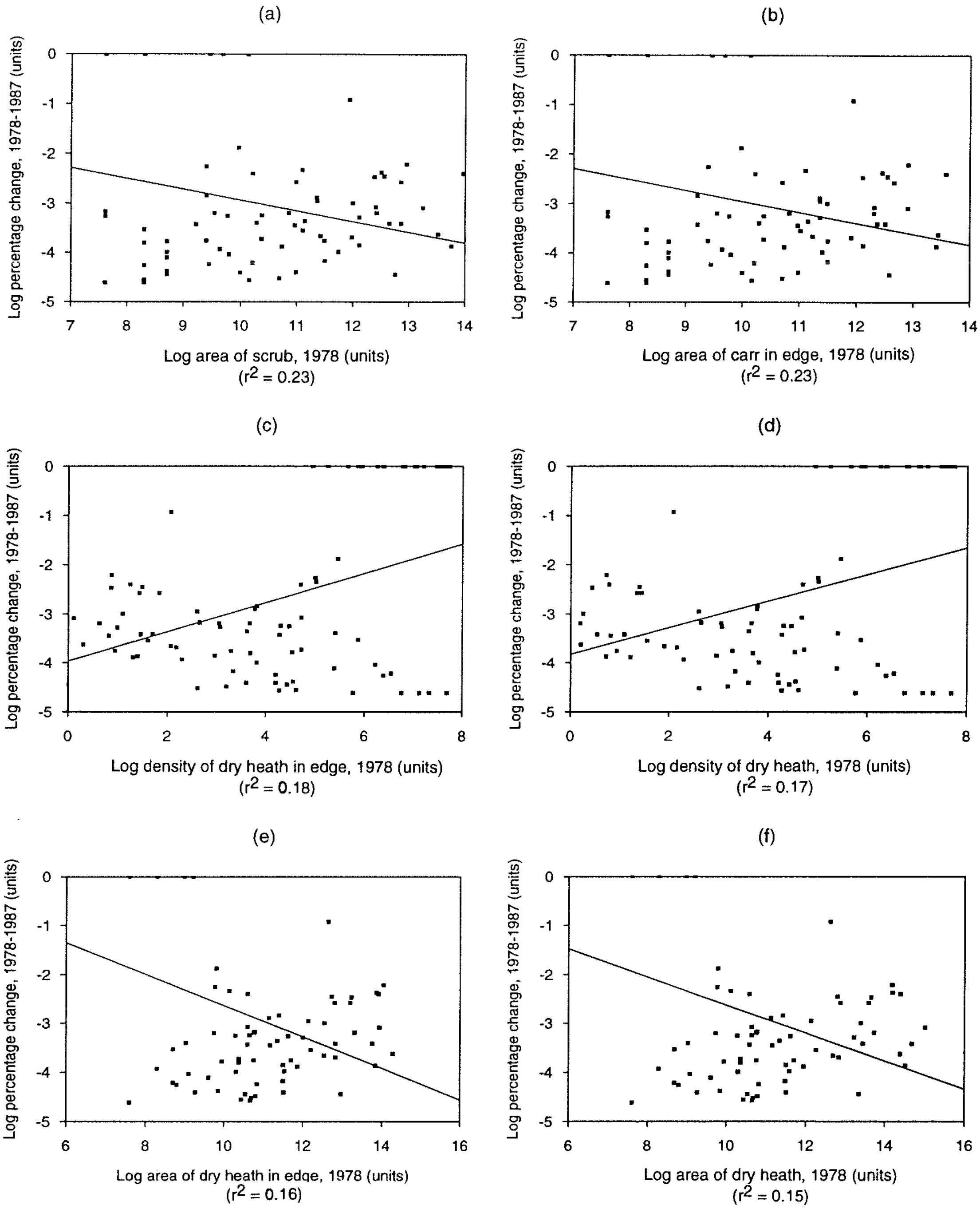


Fig. 4.19 Scatterplots of (a) log percentage change in area of dry heath, 1978-1987 against log area of scrub, 1978; (b) log percentage change in area of dry heath, 1978-1987 against log area of carr in the edge, 1978; (c) log percentage change in area of dry heath, 1978-1987 against log density of dry heath in the edge, 1978; (d) log percentage change in area of dry heath, 1978-1987 against log density of dry heath, 1978; (e) log percentage change in area of dry heath, 1978-1987 against log area of dry heath in the edge, 1978; (f) log percentage change in area of dry heath, 1978-1987 against log area of dry heath, 1978.

4.7.3.2 Multiple regression for dry heath, 1978-1987

Percentage change in area of dry heath between 1978 and 1987 was most highly correlated with the area of carr in the edge of a patch (Table 4.9). The area of scrub in the edge of a patch accounted for a significant part of the residuals (demonstrating that scrub and carr act relatively independently), and two further variables accounted for a significant portion of the remainder of the residuals. These were the ratio of density of dry heath to humid heath in a patch and the ratio of dry heath to carr in the edge of a patch. The area of carr and scrub in the edge of a patch influenced percentage change. Therefore, when the influence of area of carr in the edge of a patch was removed, the area of scrub in the edge still accounted for a significant amount of the variation in percentage change (5%). The coefficient of determination was reasonably large ($r^2 = 0.32$) and, therefore, the multiple regression equation could be considered for use as a predictor of change. The regression equation is as follows:

Log (percentage change) = 0.7 + 0.3 log (area of carr in the edge of a patch) + 0.1 log (area of scrub in the edge of a patch) + 1.7 log (ratio of density of dry heath to humid heath) + 0.1 log (ratio of area of dry heath to carr in the edge of a patch).

The equation can be used to account for 32% of the variation in percentage change in area of dry heath between 1978 and 1987. It could be used to predict in the future if it can be assumed that set of the relations modelled by the equation are constant over time.

Table 4.9. Multiple regression for patch-based primary categories, 1978.

Logged, patch-based explanatory variables	*df*	*p*	r^2
Area of carr in the edge of patch	1, 85	2.01e-o	0.23
+ Area of scrub in the edge of patch	2, 84	1.15e-0	0.28
+ Density of dry heath : humid heath	3, 83	1.34e-0	0.30
+ Area of dry heath : carr in the edge	4, 82	1.51e-0	0.32

4.7.3.3 Simple regression for wet heath, 1978-1987

The relationships between percentage change in area of wet heath between 1978 and 1987 and each independent variable were examined using simple regression. None of the independent variables were significant in accounting for the variation in percentage change in area of wet heath over time. The highest coefficient of determination resulted when percentage change was regressed on the area of wet heath in the edge of a patch ($r^2 = 0.08$). It is most likely that the relationships involving wet heath are obscured by those involving the more widespread dwarf shrub vegetation types.

4.7.3.4 Simple regression for humid heath, 1978-1987

Simple regression resulted in eight attributes accounting for significant amounts of variation in percentage change of humid heath between 1978 and 1987 (Table 4.10). Percentage change in area of humid heath was relatively highly correlated with both area of humid heath in the edge of a patch ($r^2 = 0.16$) and with area of humid heath in the whole of a patch ($r^2 = 0.15$). However, these were both inversely related with percentage change in area of humid heath, which was the converse of the hypothesised relationship (Fig. 4.20a & Fig. 4.20b). Similarly, the ratio of area of humid heath to wet heath had a negative relationship with percentage change. The remaining significant relationships all supported the hypotheses. A greater density of humid heath in a patch as a whole or in the edge made it less susceptible to change, that is, the less fragmented the area of humid heath in a patch is, the less susceptible it is to change (Figs. 4.20c). Attributes describing the area (or relative areas) of invasive species (woodland and scrub) were also negatively related with percentage change (see Fig. 4.20d). Greater areas of scrub caused greater losses in area of humid heath.

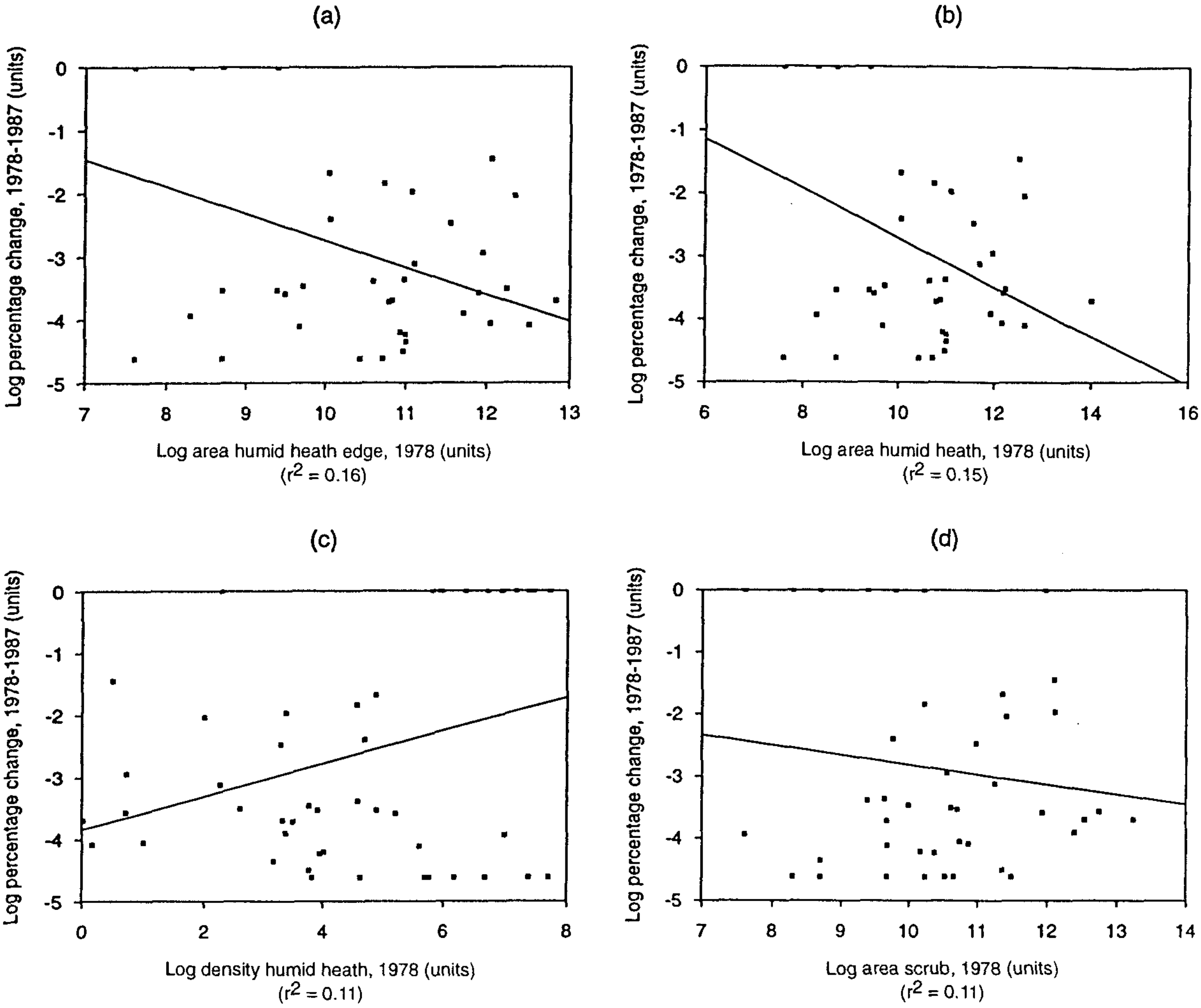


Fig. 4.20 Scatterplots of (a) log percentage change in area of humid heath, 1978-1987 against log area of humid heath in the edge of a patch, 1978; (b) log percentage change in area of humid heath, 1978-1987 against log area of humid heath, 1978; (c) log percentage change in area of humid heath, 1978-1987 against log density of humid heath, 1978; (d) log percentage change in area of humid heath, 1978-1987 against log area of scrub, 1978.

Table 4.10. Simple regression for percentage change in area of humid heath versus patch-based primary categories, 1978. Only the significant relationships are shown.

Logged, patch-based, explanatory variables	*df*	*p*	r^2	Ho / H_1	Relationship
Area of humid heath	1, 48	0.0053	0.15	Ho	Negative
Area of scrub	1, 48	0.0209	0.11	H_1	Negative
Density of humid heath	1, 48	0.0163	0.11	H_1	Positive
Area of humid heath in the edge of a patch	1, 48	0.0040	0.16	Ho	Negative
Density of humid heath in the edge	1, 48	0.0145	0.12	H_1	Positive
Area of humid heath : wet heath in the edge	1, 48	0.4529	0.12	-	Negative
Area of humid heath : scrub in the edge	1, 48	0.0216	0.11	Ho	Positive
Area humid heath : woodland	1, 48	0.0203	0.11	Ho	Positive

4.7.3.5 Multiple regression to examine percentage change in area of humid heath, 1978-1987

Multiple regression resulted in percentage change in area of humid heath being significantly correlated with three variables (Table 4.11). The density of humid heath in the edge of a patch accounted for most variation in percentage change. Density of scrub in the edge of a patch accounted for a significant part of the residuals and the ratio of density of humid heath to scrub in the edge of a patch accounted for a significant amount of the remainder. Percentage change was most correlated with the density of humid heath in the edge of a patch, indicating that the more fragmented the coverage of humid heath in the edge of a patch, the greater the percentage decrease in area. When the density of humid heath in the edge of a patch was held constant, percentage change was most significantly correlated with the density of scrub in the edge of a patch. The greater the density of scrub in the edge of a patch the greater the percentage change. Further, this was reflected in the relationship between percentage change and the ratio of density of humid heath to scrub in the edge of a patch. In all, percentage change in area of humid heath resulted from invasion of scrub from the edge of a patch. The multiple regression equation is as follows:

Log (percentage change) = 6.2 + 0.63 log (density of humid heath in the edge of a patch) + -9.6 log (density of scrub in the edge of a patch) + -3.4 log (ratio of density of humid heath to scrub in the edge of a patch).

Table 4.11 Multiple regression for patch-based primary categories, 1978

Logged patch-based explanatory variables	*df*	*p*	r^2
Density of humid heath in the edge	1, 48	0.014	0.12
+ Density of scrub in the edge	2, 47	0.007	0.19
+ Density of humid heath : scrub in the edge	3, 46	0.005	0.23

4.7.3.6 Simple regression for peatland, 1978-1987

Finally, percentage change in area of peatland between 1978 and 1987, was regressed on each explanatory variable. Percentage change was significantly correlated with a single variable: the ratio of area of peatland to scrub in the edge of a patch (Table 4.12). The relationship was positive and, therefore, as anticipated (Fig. 4.21). Despite the low correlation, this supported the hypothesis that there would be less percentage decrease in area of peatland as the area of peatland increased and the area of invasive species decreased in the edge of a patch. Further, the relationship indicated that succession played a part in causing change in area of peatland. However, as a 95% confidence interval was used and as twenty explanatory variables were used in the analysis and a single significant relationship resulted, the relationship could easily have occurred though chance.

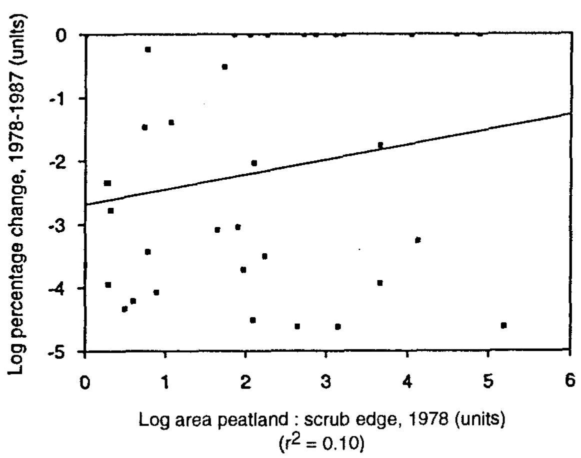


Fig. 4.21 Scatterplot of log percentage change in area of peatland, 1978-1987 against log ratio of area of peatland to scrub in the edge of a patch, 1978.

Table 4.12. Simple regression for percentage change in area of peatland versus patch-based primary categories, 1978. Only the significant relationships are shown.

Logged, patch-based, explanatory variables	*df*	*p*	r^2	Ho / H_1	**Relationship**
Area of peatland : scrub in the edge	1, 40	0.0203	0.10	H_1	Positive

4.7.3.7 Multiple regression to examine percentage change in area of peatland, 1978-1987

Percentage change in area of peatland was most highly correlated with the ratio of area of peatland to scrub in the edge of a patch, but interestingly, the ratio of peatland to carr accounted for a significant part of the residuals. Therefore, the greater the area of invasive species (such as scrub and carr) compared to the area of peatland in the edge of a patch, the more susceptible the patch is to invasion. Percentage change was significantly correlated with the ratio of area of peatland to carr when the ratio of peatland to scrub in the edge was held constant.

Table 4.13. Multiple regression for patch-based primary categories, 1978

Logged patch-based explanatory variables	*df*	*p*	r^2
Area of peatland : scrub in the edge	1, 40	0.036	0.10
+ Area of peatland : carr in patch	2, 39	0.056	0.14

4.7.4 Regression for the secondary categories, 1978-1987

There were no significant simple regression results when percentage change in area of dwarf shrub vegetation was regressed against each of the explanatory variables at the secondary category level. It is likely that the low signal-to-noise ratio accounts for the lack of significant relationships at the secondary category level.

4.7.5 Regression results for the aggregated primary categories, 1987-1996

Regression analysis was carried out at the aggregated primary, primary and secondary category levels to indicate which explanatory variables best accounted for percentage change in area of dwarf shrub vegetation between 1987 and 1996.

4.7.5.1 Simple regression for the aggregated primary categories, 1987 - 1996

Two significant relationships resulted when simple regression was carried out at the aggregated primary category level (Table 4.14). Percentage change was significantly correlated with the area of invasive species in a patch. As the area of invasive species increased, percentage change decreased, so that the inverse relationship was contrary to that hypothesised (Fig. 4.22a). Percentage change was similarly related with the area of invasive species in the edge of a patch (Fig. 4.22b). There was no apparent reason for both inverse relationships. However, the coefficients of determination were small ($r^2 = 0.06$). Multiple regression was not carried out because of the small coefficient of determination.

Table 4.14. Simple regression for patch-based aggregated primary categories, 1987. Only the significant relationships are shown.

Logged patch-based, explanatory variables	*df*	*p*	r^2	*Ho* / H_1	Relationship
Area of invasive species in a patch	1, 80	0.0325	0.06	*Ho*	Positive
Area of invasive species in the edge	1, 80	0.0311	0.06	*Ho*	Positive

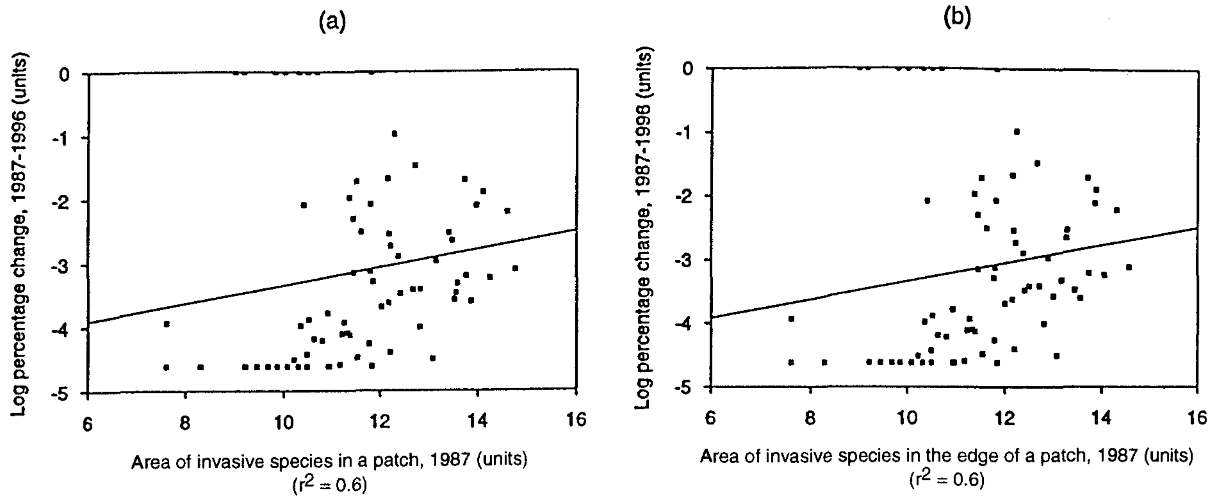


Fig. 4.22 Scatterplots of (a) log percentage change in area of dwarf shrub vegetation, 1987-1996 against log area of invasive species, 1987; (b) log percentage change in area of dwarf shrub vegetation, 1987-1996 against log area of invasive species, in the edge of a patch 1987.

4.7.6 Regression for the primary categories, 1987-1996

Simple and multiple regression were carried out at the primary category level for 1987 to 1996.

4.7.6.1 Simple regression for dry heath, 1987-1996

Percentage change in area of dry heath between 1987 and 1996 was correlated with each explanatory variable. It appeared that percentage change in area of dry heath between 1987 and 1996 could not be accounted for by any of the selected variables, the highest coefficient of determination being 0.05. Again, multiple regression was not carried out because of the small coefficients of determination.

4.7.6.2 Simple regression for wet heath, 1987-1996

Percentage change in area of wet heath between 1987 and 1996 was correlated with three explanatory variables (Table 4.15). The ratio of wet heath to scrub in the edge of a patch accounted for most variation in percentage change (r^2 = 0.12). The positive relationship was as hypothesised (Figs. 4.23a). Percentage change was similarly correlated with the ratio of wet heath to scrub in the edge of a patch (Fig. 4.23b) and the ratio of area of wet heath to carr in a patch (Fig. 4.23c). Despite the low correlations, succession appeared to cause a significant amount of change in area of wet heath between 1987 and 1996. Percentage change lessened as the area of wet heath in a patch increased. That is, greater areas of wet heath in a patch were less susceptible to change.

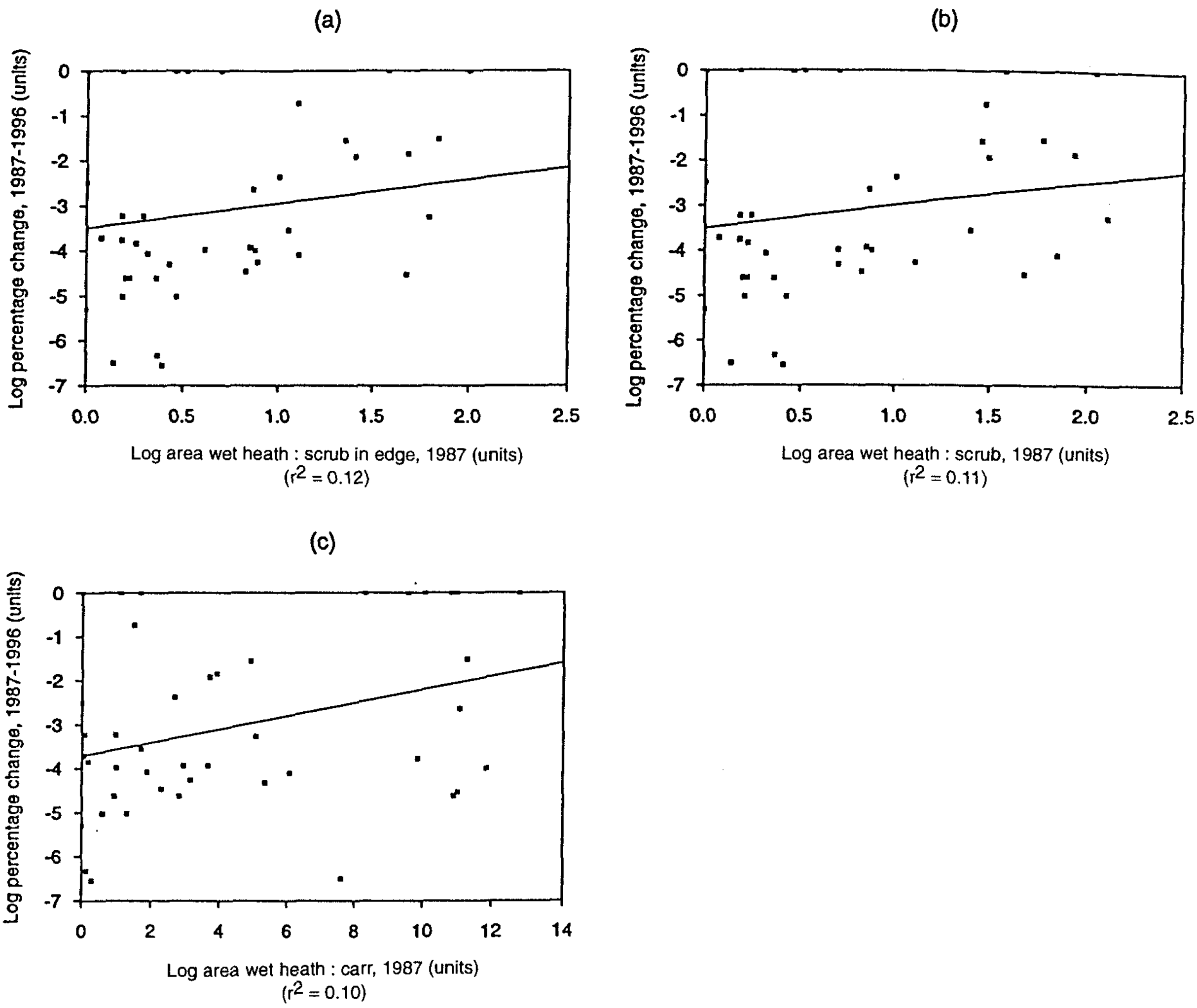


Fig. 4.23 Scatterplots of (a) log percentage change in area of wet heath, 1987-1996 against log ratio of area of wet heath to scrub in the edge of a patch, 1987; (b) log percentage change in area of wet heath, 1987-1996 against log ratio of area of wet heath to scrub, 1987; (c) log percentage change in area of wet heath, 1987-1996 against log ratio of area of wet heath to carr, 1987.

Table 4.15. Simple regression results for percentage change in area of wet heath versus patch-based primary categories, 1987. Only the significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2	Ho / H_1	**Relationship**
Area of wet heath : scrub in a patch	1, 41	0.0264	0.11	H_1	Positive
Area of wet heath : carr in a patch	1, 41	0.0345	0.10	H_1	Positive
Area of wet heath : scrub in the edge	1, 41	0.0224	0.12	H_1	Positive

4.7.6.3 Multiple regression for wet heath, 1987-1996

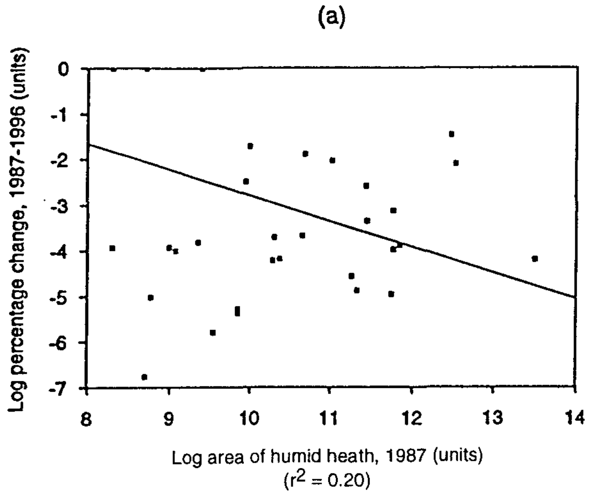
Percentage change in area of wet heath was most highly correlated with the ratio of wet heath to scrub in the edge of a patch. The area of humid heath in a patch accounted for a significant part of the residuals (Table 4.16). In this case, the area of wet heath relative to the area of scrub in the edge of a patch influenced percentage change the most. Percentage change was significantly correlated with the area of humid heath when the ratio of wet heath to scrub in the edge was held constant. This may indicate changes between wet heath and humid heath. Rose *et al.*, (1999) describe how dwarf shrub vegetation may switch between types.

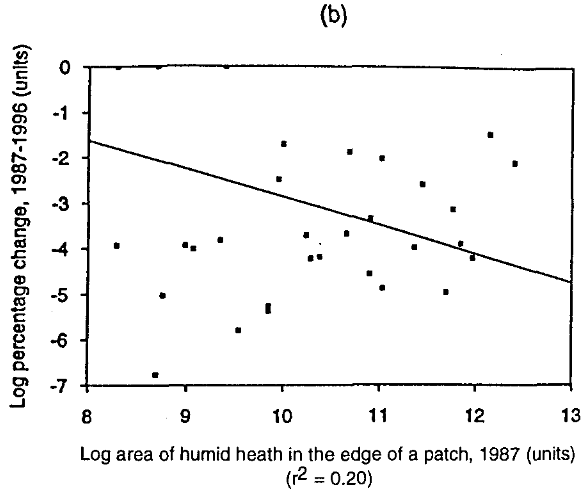
Table 4.16. Multiple regression for patch-based primary categories, 1987.

Logged patch-based explanatory variables	*df*	*p*	r^2
Area of wet heath : scrub in the edge	1, 41	0.022	0.12
+ Area of humid heath in patch	2, 40	0.011	0.20

4.7.6.4 Simple regression for humid heath, 1987-1996

Percentage change in area of humid heath was correlated with thirteen explanatory variables (Table 4.17). Percentage change was most highly correlated with the area of humid heath in a patch (r^2 = 0.20) and the area of humid heath in the edge of a patch (r^2 = 0.20). Both relationships were positive and the converse of those hypothesised (Fig. 4.24a & Fig. 4.24b). However, percentage change was positively correlated with the density of humid heath in a patch (Fig. 4.24c). As hypothesised, percentage change decreased as density increased. This may be interpreted to mean that the less fragmented the area of humid heath, the less susceptible it was to change. Of the remaining significant relationships the inverse relationships between percentage change and area (or proportion) of invasive species (scrub and carr) were as hypothesised. However, several significant relationships were not as hypothesised including the shape of a patch and the density of humid heath in the edge of a patch. The relationships between percentage change and area of wet heath in a patch and the edge of a patch had not been hypothesised. Clearly, transitions between dwarf shrub vegetation types caused change.





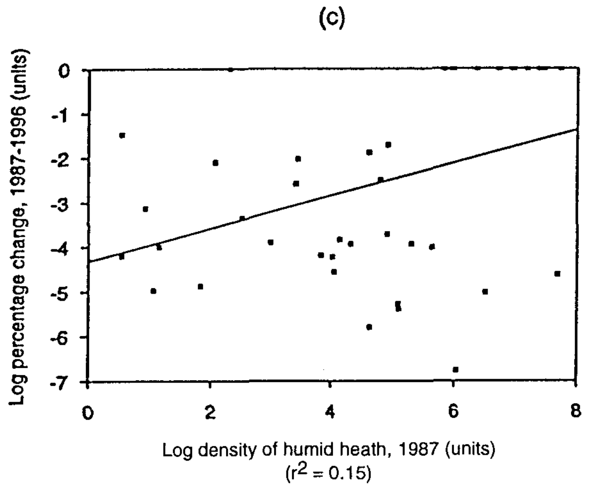


Fig. 4.24 Scatterplots of (a) log percentage change in area of humid heath, 1987-1996 against log area of humid heath, 1987; (b) log percentage change in area of humid heath, 1987-1996 against log area of humid heath in the edge of a patch, 1987; (c) log percentage change in area of humid heath, 1987-1996 against log density of humid heath in the edge of a patch, 1987.

Table 4.17. Simple regression for percentage change in area of humid heath versus patch-based primary categories, 1987. Only the significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2	*H*o / H_1	Relationship
Area of wet heath in a patch	1, 40	0.0186	0.13	-	Negative
Area of humid heath in a patch	1, 40	0.0033	0.20	*H*o	Negative
Area of scrub in a patch	1, 40	0.0309	0.11	H_1	Negative
Area of carr in a patch	1, 40	0.0295	0.11	H_1	Negative
Density of humid heath in a patch	1, 40	0.0108	0.15	H_1	Positive
Area of wet heath in the edge of a patch	1, 40	0.0181	0.13	-	Negative
Area of humid heath in the edge of a patch	1, 40	0.0030	0.20	*H*o	Negative
Area of scrub in the edge of a patch	1, 40	0.0301	0.11	H_1	Negative
Area of carr in the edge of a patch	1, 40	0.0214	0.13	H_1	Negative
Density of humid heath in the edge	1, 40	0.0117	0.15	*H*o	Negative
Area of humid heath : carr in the edge	1, 40	0,029	0.11	H_1	Positive

4.7.6.5 Multiple regression for humid heath, 1987-1996

Multiple regression (in which the *H*o variables were excluded) reduced the number of significant relationships considerably (Table 4.18). Percentage change in area of humid heath was most highly correlated with the density of humid heath in a patch. The density of woodland accounted for a significant part of the residuals with the ratio of area of humid heath to carr accounted for a significant part of the remainder. Finally, the area of scrub in the edge of a patch accounted for a significant part of the remaining remainder. Percentage change was correlated with the density of woodland when the effect of density of humid heath was held constant. Therefore, fragmentation, both of the coverage of humid heathland or the woodland, caused change. When the effect of fragmentation was removed, the ratio of area of humid heath to carr and scrub in the edge of a patch were significant. The multiple regression equation could be used for prediction. However, the prediction may not be accurate because of the small coefficient of determination ($r^2 = 0.35$). The equation is as follows:

Log (percentage change) = 4.4 + 0.5 log (density of humid heath) + 4.2 log (density of woodland) + 0.1 log (ratio of area of humid heath to carr in the edge of a patch) + 0.1 log (area of scrub in the edge of a patch)

Table 4.18. Multiple regression for patch-based primary categories, 1987.

Logged patch-based explanatory variables	*df*	*p*	r^2
Density of humid heath in patch	1, 40	0.010	0.15
+ Density of woodland in patch	2, 39	0.003	0.26
+ Area of humid heath : carr in the edge	3, 38	0.002	0.31
+ Area of scrub in the edge	4, 37	0.003	0.35

4.7.6.6 Simple regression for peatland, 1987-1996

Finally, percentage change in area of peatland was correlated with each explanatory variable (Table 4.19). The variable most highly correlated with percentage change was the ratio of area of peatland to carr in a patch ($r^2 = 0.39$). The positive relationship was as hypothesised: percentage change decreased as the area of peatland in a patch increased relative to the area of carr (Fig. 4.25a). Percentage change was also significantly and negatively correlated with area of carr (Fig. 4.25b). As hypothesised, the greater the area of carr in a patch, the greater the percentage change in area of peatland. Percentage change was similarly inversely related with the area of carr in the edge of a patch (Fig. 4.25c). Consistently, carr appeared to be the invasive species type which caused most change in area of peatland.

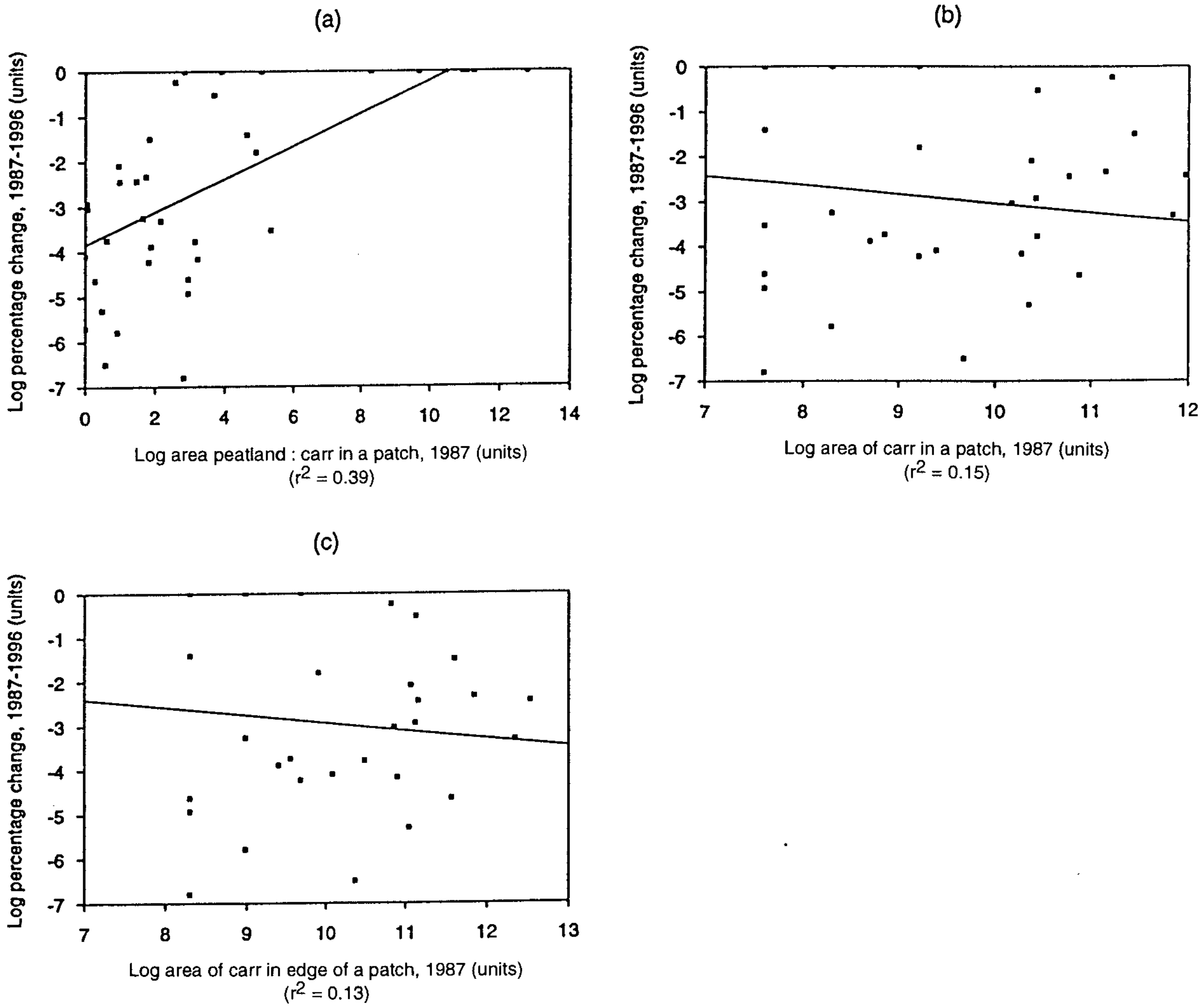


Fig. 4.25 Scatterplots of (a) log percentage change in area of peatland, 1987-1996 against log ratio of area of peatland to carr, 1987; (b) log percentage change in area of peatland, 1987-1996 against log area of carr, 1987; (c) log percentage change in area of peatland, 1987-1996 against log area of carr in the edge of a patch, 1987.

Table 4.19. Simple regression for percentage change in area of peatland versus patch-based primary categories, 1987. Only the significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2	*Ho* / *H1*	**Relationship**
Area of carr in a patch	1, 37	0.0135	0.15	*H1*	Negative
Area of carr in the edge of a patch	1, 37	0.0208	0.13	*H1*	Negative
Area of peatland : carr in a patch	1, 37	2.16e-05	0.39	*H1*	Positive

4.7.6.7 Multiple regression for peatland, 1987-1996

Percentage change in area of peatland was most highly correlated with the ratio of area of peatland to carr in a patch (Table 4.20). The density of peatland in the edge of a patch accounted for a significant part of the residuals. The area of peatland relative to the area of carr in a patch influenced change. When held constant, the density of peatland in the edge of a patch, or the degree of fragmentation of the edge of a patch, also influenced change. Again, the multiple regression equation could be used for predictive purposes. The relatively large coefficient of determination indicates that this can account for 48% of the variation in percentage change in area of peatland. However, the equation should be used with caution. The multiple regression equation is as follows:

Log (percentage change) = 0.4 + 0.5 log (ratio of area of peatland to carr in a patch) + 0.5 log (density of peatland in the edge of a patch)

Table 4.20. Multiple regression for patch-based primary categories, 1987.

Logged patch-based explanatory variables	*df*	*p*	r^2
Area of peatland : carr	1, 37	2.16e-05	0.39
+ Density of peatland in the edge	2, 36	8.70e-06	0.48

4.7.7 Regression results for the secondary categories, 1987-1996

There were no significant simple regression results when percentage change in area of dwarf shrub vegetation was regressed against each of the explanatory variables at the secondary category level. This was most likely the result of a low signal-to-noise ratio.

4.8 Summary and discussion

It was hypothesised that percentage change was influenced by several factors and these factors formed a list of explanatory variables (see Chapter 3, 3.5.2). Initially, areal change in dwarf shrub vegetation, invasive species and 'others' (*i.e.*, land use change) were examined. Between 1978 and 1987 the area of dwarf shrub vegetation decreased by 532 km^2. The most likely cause of the decline was land use change (the area of 'others' increased by 417 km^2). The area of grassland (344 km^2), agriculture (138 km^2) and houses and gardens (144 km^2) increased substantially. The area of invasive species rose by 119 km^2 indicating that some of the decline in area of dwarf shrub vegetation may have resulted from succession.

Between 1987 and 1996 the area of dwarf shrub vegetation continued to decrease (- 756 km^2). However, the area of 'others' also decreased substantially (- 698 km^2). In contrast, the area of invasive species increased by 1,454 km^2. Despite the apparent reversal of the trend towards an increase in changes in land use, the area of grassland continued to increase (332 km^2), but the area of agriculture (- 373 km^2) and houses and gardens (- 237 km^2) decreased (although the fall in area of houses and gardens cannot be readily accounted for).

It is clear that area of dwarf shrub vegetation was declining rapidly. Between 1978 and 1987 the major cause of the decline was change in land use. Between 1987 and 1996 succession was the major cause of change. Land use change, unlike succession, can occur anywhere, irrespective of initial land cover or land use type. The reasons for the apparent decrease in land use change between 1987 and 1996 were not clear. One possible explanation is that legislation protecting the heaths implemented in the mid 1980s (in particular, changes in the European Agricultural Policy whereby land was set aside from agricultural production (Veitch *et al.*, 1995)), may have protected the dwarf shrub vegetation from land use change. Despite the decline in area lost due to changing land use between 1987 and 1996, the substantial increase in area of invasive species meant that the area of dwarf shrub vegetation lost between 1987 and 1996 exceeded that lost between 1978 and 1987.

Simple regression resulted in several significant variables accounting for percentage change. The analysis appeared to support several of the initial hypotheses that percentage change was influenced by several variables including the initial area of dwarf shrub vegetation in a patch (Table 4.21). However, the coefficients of determination were often quite small.

The regression results may be divided into three (Table 4.21). Firstly, percentage change (at both the aggregated primary and primary levels) was in several cases significantly related with the density of dwarf shrub vegetation (or dwarf shrub vegetation type) in a patch, or the edge of a patch. Secondly, percentage change was in several cases significantly related with

Table 4.21 Summary of significant relationships from simple regression. ♣ indicates that the hypothesis has been accepted, ♦ indicates that the relationship is significant but was contrary to that hypothesised.

Response variable: %change in area of heath			**Response variable: %change in heath type**	**Dry Heath**		**Wet Heath**		**Humid Heath**		**Peatland**	
Explanatory variables	H_1 78-87	H_1 87-96	**Explanatory variables**	H_1 78-87	H_1 87-96	H_1 78-87	H_1 87-96	H_1 78-87	H_1 87-96	H_1 78-87	H_1 87-96
1. Area of heath			Area of dry heath	♦							
			Area of wet heath								
			Area of humid heath					♦	♦		
			Area of peatland								
2. Area of invasive species		♦	Area of scrub	♣				♣	♣		
			Area of carr						♣		♣
			Area of woodland	♣							
3. Area of 'others'											
4. Density of heath	♣		Density of dry heath	♣							
			Density of wet heath								
			Density of humid heath					♣	♣		
			Density of peatland								
5. Density of invasive species	♣		Density of scrub								
			Density of carr								
			Density of woodland								
6. Density of 'others'											
7. Area of heath in edge	♣		Area of dry heath in edge	♦							
			Area of wet heath in edge								
			Area of humid heath in edge					♦	♦		
			Area of peatland in edge								
8. Area of invasive species in edge		♦	Area of scrub in edge	♣					♣		
			Area of carr in edge	♣					♣		♣
			Area of woodland in edge								
9. Area of 'others' in edge											
10. Patch context			Patch context								
11. Density of heath in edge	♣		Density of dry heath in edge	♣							
			Density of wet heath in edge								
			Density of humid heath in edge					♣	♦		
			Density of peatland in edge								
12. Density of invasive species in edge			Density of scrub in edge of patch								
			Density of carr in edge of patch								
			Density of woodland in edge of patch								
13. Density of 'others' in edge											
			Area of heath:dry heath								
			Area of heath:wet heath								
			Area of heath:humid heath								
			Area of heath:peatland								
14. Area of heath:invasive species			Area of heath:scrub	♣			♣				
			Area of heath:carr				♣				♣
			Area of heath:woodland								
15. Area of heath:'others'											
			Density heath:dry heath								
			Density heath:wet heath								
			Density heath:humid heath								
			Density heath:peatland								
			Density heath:dry heath in edge								
			Density heath:wet heath in edge								
			Density heath:humid heath in edge								
			Density heath:peatland in edge								
			Density heath:scrub								
			Density heath:carr								
			Density heath:woodland					♦			
			Density heath:scrub in edge								
			Density heath:carr in edge								
			Density heath:woodland in edge								
			Area of heath:dry heath in edge								
			Area of heath:wet heath in edge								
			Area of heath:humid heath in edge								
			Area of heath:peatland in edge								
16. Area of heath:area of invasive species in edge			Area of heath:scrub in edge				♣	♦		♣	
			Area of heath:carr in edge						♣		
			Area of heath:woodland in edge								
17. Area of heath:area of 'others' in edge											
18. Area of a patch											
19. Length of the perimeter											
20. Shape of patch											

the area of invasive species (or invasive species type) in a patch, or the edge of a patch. Thirdly, percentage change at the primary category level was significantly related with the ratio of area of dwarf shrub vegetation type to the area of invasive species type in a patch or in the edge of a patch.

Density corresponds to the degree of within-patch fragmentation. It was hypothesised that the greater the density of dwarf shrub vegetation in a patch, the less susceptible a patch would be to change, and this appeared to be so. Further, the greater the density of dwarf shrub vegetation in the edge of a patch, the less likely it was for invasion to occur. Again, this hypothesis appeared to be supported. When the coverage of dwarf shrub vegetation in patch was not dense the patch was internally fragmented. An internally fragmented patch contains areas of invasive species (or 'others'), which may lead to increasing pressure from invasion from within the patch. The same is true of density of dwarf shrub vegetation in the edge of a patch. When the coverage of dwarf shrub vegetation in the edge of a patch is dense there are few areas of non-heathland species. Invasion can only occur in the presence of an available seed source. When a patch is not fragmented there are few such seed sources, making the patch less susceptible to change.

The area of invasive species in a patch also influenced percentage change. Invasion, it was hypothesised, occurred from outside a patch. Therefore, edges would be expected to influence change, and this appeared to be so. The smaller the area of invasive species in the edge of a patch, the less the pressure from succession as the seed source is limited. The significance of the relationship between percentage change and the ratio of area of dwarf shrub vegetation to area of invasive species in the edge of a patch illustrated the constancy of the relationship between percentage change and the area of dwarf shrub vegetation and invasive species in a patch. Also, it implied that the establishment of species from the seedbank had little influence on change as succession appeared to depend on the area of invasive species in a patch or in the edge of a patch.

Although several hypotheses were supported, several were also rejected. In particular, the effect of patch context on percentage change was rejected. It was hypothesised that context, or 'what surrounded a patch' would influence change. A Landsat TM image (see Chapter 3, 3.3.2) provided the necessary contextual information. Context may not have proved significant for several reasons. First, the image may not have been classified accurately. Second, the patches may not reflect reality, and if this was so then context could not influence percentage change.

Percentage change was consistently inversely correlated with the area of dwarf shrub vegetation type in a patch. Although the relationship was in many cases significant, it was the opposite of that hypothesised. Such inverse relationships may have resulted because the larger the area of dwarf shrub vegetation type, the greater the chance that it is a patch itself (rather than a patch within a larger overall dwarf shrub vegetation patch), and hence the greater the chance of being surrounded by invasive species.

Several significant relationships had not been hypothesised. In particular, the effect of each dwarf shrub vegetation type on percentage change in each other. For example, percentage change in area of dry heath (between 1978 and 1987) was significantly related with the ratio of area of dry heath to humid heath. This implied that the area of dry heath was related to the area of humid heath in some way. Climate change may cause fluctuations in area of each dwarf shrub vegetation type. For example, in a particularly wet year, the border between humid and dry heath may become blurred with dry heath in some circumstances becoming humid heath. This may account for such a relationship. Also, the gradient between what can be defined as dry heath and what can be defined as humid heath is not clear-cut especially as warm weather can dry out the more humid heaths out. Therefore, errors in the survey could also account for the relationship.

Despite the areal analysis of change revealing that changing land use, particularly between 1978 and 1987, appeared to cause change, multiple regression only once indicated that percentage change in area of dwarf shrub vegetation was significantly correlated with land use (the ratio of area of dwarf shrub vegetation to 'others'). It was clear from the maps (Figs. 4.3-4.16) that changes in land use occurred across many patches and its influence could not be isolated and removed (see Appendix 4). If patches of heath are being turned to grassland then it is unreasonable to expect a significant ecological relationship between percentage change and the explanatory variables. The fact that 'others' did not prove significant when simple regression was carried out is because change between 1978 and 1987 is not related to the state of land use in 1978, that is, anthropogenic activity is not predictable.

The often small coefficients of determination could also be the result of two patch related factors. First, it is reasonable that different patterns of change may exist for different patch sizes. However, an investigation of the relationship indicated this was not so (Appendix 5). Second, the patches may not have been an adequate reflection of reality. However, the patch-based approach is itself flawed as all patches, irrespective of size are fragmented, that is, they are made of several patches, or even individual species. Perhaps a patch-based approach to examining change in the dwarf shrub vegetation should, in certain circumstances, be questioned. It is suggested that the patch-based analysis is too high-level or generalised and the focus should be brought in to examine change at a lower level (pixel-based analysis).

It is clear that on a patch basis, the explanatory variables chosen to explain percentage change in area of dwarf shrub vegetation (or dwarf shrub vegetation type) produced coefficients of determination that were quite often small. This was probably the result of noise due to the influence of 'others' and competition between dwarf shrub vegetation types. Despite the obvious influence of other factors (such as changes in land use and competition between heath species), the signal due to succession remained.

4.9 Conclusion

It was clear that change was occurring and for the area of dwarf shrub vegetation in a patch, change continued in the same direction towards a decline in area. Changing land use played a part in the decline particularly between 1978 and 1987 but between 1987 and 1996 its effect dwindled. Natural effects also caused change in area of dwarf shrub vegetation. The effect of succession appeared to increase over time. Despite the obvious influence of changing land use, the significance of the relationship between percentage change and area of invasive species remained clear. The coefficients of determination were often small, but this was the result of noise caused by factors such as changing land use, the effect of which could not be removed.

It was hypothesised that several factors influenced percentage change in area of dwarf shrub vegetation. In particular, the density of dwarf shrub vegetation (and dwarf shrub vegetation type) in a patch and in the edge of a patch, area of invasive species (or invasive species type) in a patch and in the edge of a patch and the ratio of dwarf shrub vegetation to invasive species in a patch and in the edge of a patch had the greatest influence on percentage change. Several attempts to increase the coefficients of determination did not succeed. Despite the often small coefficients of determination, the relationship between percentage change, degree of fragmentation of the area of dwarf shrub vegetation in a patch and the area of invasive species in a patch was clear.

In the next chapter, a pixel-based analysis is undertaken allowing comparisons between the patch-based and pixel-based approaches to be made.

CHAPTER 5

PIXEL-BASED ANALYSIS

5.1 Introduction

In this chapter, a pixel-based perspective was taken. The rationale for taking a pixel-based approach was that it was reasonable that change occurred at a sub-patch level as patches are themselves internally fragmented. The analysis presented in this chapter comprises several stages. First, histograms of some of the data were plotted. Second, feature space plots were examined. Third, a spatial element was added by mapping change. Finally, a statistical model of change was developed using both simple regression and multiple regression modelling techniques.

5.2 The pixel-based perspective

As in the per-patch analysis, simple regression provided the basis for the per-pixel analysis (see Chapter 2, 2.4.3). The initial choice of explanatory variables altered, but remained determined by hypotheses based on ecological processes driving a dwarf shrub vegetation system. Indices of patch geometry and densities of vegetation types were no longer included. The explanatory variables were defined based on the properties identified as the most likely to influence percentage change in area of dwarf shrub vegetation (Chapter 2, 2.3.1). That is, variables were chosen because they were deemed of most ecological relevance and because it was hypothesised that each would have an effect on the percentage change in the area of dwarf shrub vegetation in a pixel. The explanatory variables tested hypotheses based on the area of individual and grouped species and ratios of area of dwarf shrub vegetation (or dwarf shrub vegetation type) to other vegetation types, and on percentage change in area of dwarf shrub vegetation over time (Table 5.1). Further, explanatory variables based on pixel context were selected. These were the density of invasive species surrounding a pixel and the distance a pixel lay from the edge. The area of invasive species in a moving window around a pixel was examined using kernel sizes ranging between 200 m and 800 m (see Appendix 6 for the necessary code). Distance from the edge was calculated using a Euclidean distance GIS function.

Table 5.1 Hypotheses tested using explanatory variables.

Heathland variables to test their influence on the process of succession	**Hypotheses tested**
1. Area of heath in pixel	The greater the area of heath, the smaller the decrease in heath as a percentage over time
2. Area of invasive species in pixel	The greater the area of invasive species, the greater the decrease in heath as a percentage over time
3. Ratio of area of heath to invasive species in pixel	The greater the area of heath to invasive species, the smaller the decrease in heath as a percentage over time
4. Density of invasive species surrounding a pixel (within a 200 m - 800 m radius)	The greater the area of invasive species surrounding a pixel, the greater the pressure from succession resulting in increased percentage change
5. Pixel context	The greater the distance between a pixel and the edge, the less susceptible it is to change

As in the per-patch analysis, the change of interest is ecological change, that is, change in area of dwarf shrub vegetation caused by ecological succession as opposed to change due to land use change and management practices. Therefore, only those pixels which either did not change or experienced a percentage decrease in area of dwarf shrub vegetation over time were included. To facilitate this, a small number of pixels which increased in area of dwarf shrub vegetation were removed.

The initial step in the per-patch analysis was to examine change over time in the areal extent of dwarf shrub vegetation. As patches were based upon an amalgamation of pixels, an areal analysis of change was unnecessary as the results would be the same (see Chapter 4, 4.3). Therefore, the first stage in the per-pixel analysis was to examine histograms for each variable in turn.

5.3 Summarising the data distributions

Histograms for each aggregated primary category explanatory variable in each of 1978, 1987 and 1996 were plotted. Several of these are shown in this section. By comparing histograms of the same variable but for different years, changes in the dispersion of data can be examined. Histograms for the primary categories are not given as the results were similar to those for the aggregated primary categories.

5.3.1 Histograms of the aggregated primary categories, 1978, 1987 and 1996

The majority of pixels contained a small area of dwarf shrub vegetation (under 10,000 m^2) (Fig. 5.1a). However, a considerable number of pixels contained medium to large areas of dwarf shrub vegetation. In 1987, the histogram remained largely unaltered (Fig. 5.1b). The majority of pixels contained an area of dwarf shrub vegetation of under 10,000 m^2. There was a reduction in the number of pixels containing medium to large areas of dwarf shrub vegetation from that in 1978. In 1996 there appeared to be little change with most pixels containing a small area of dwarf shrub vegetation (Fig. 5.1c). However, a considerable number of pixels contained an area of dwarf shrub vegetation in the region of 20,000 m^2. Overall, it was clear that the area of dwarf shrub vegetation in a pixel tended to be small and there were relatively few cells whose entire areal extent was comprised of dwarf shrub vegetation.

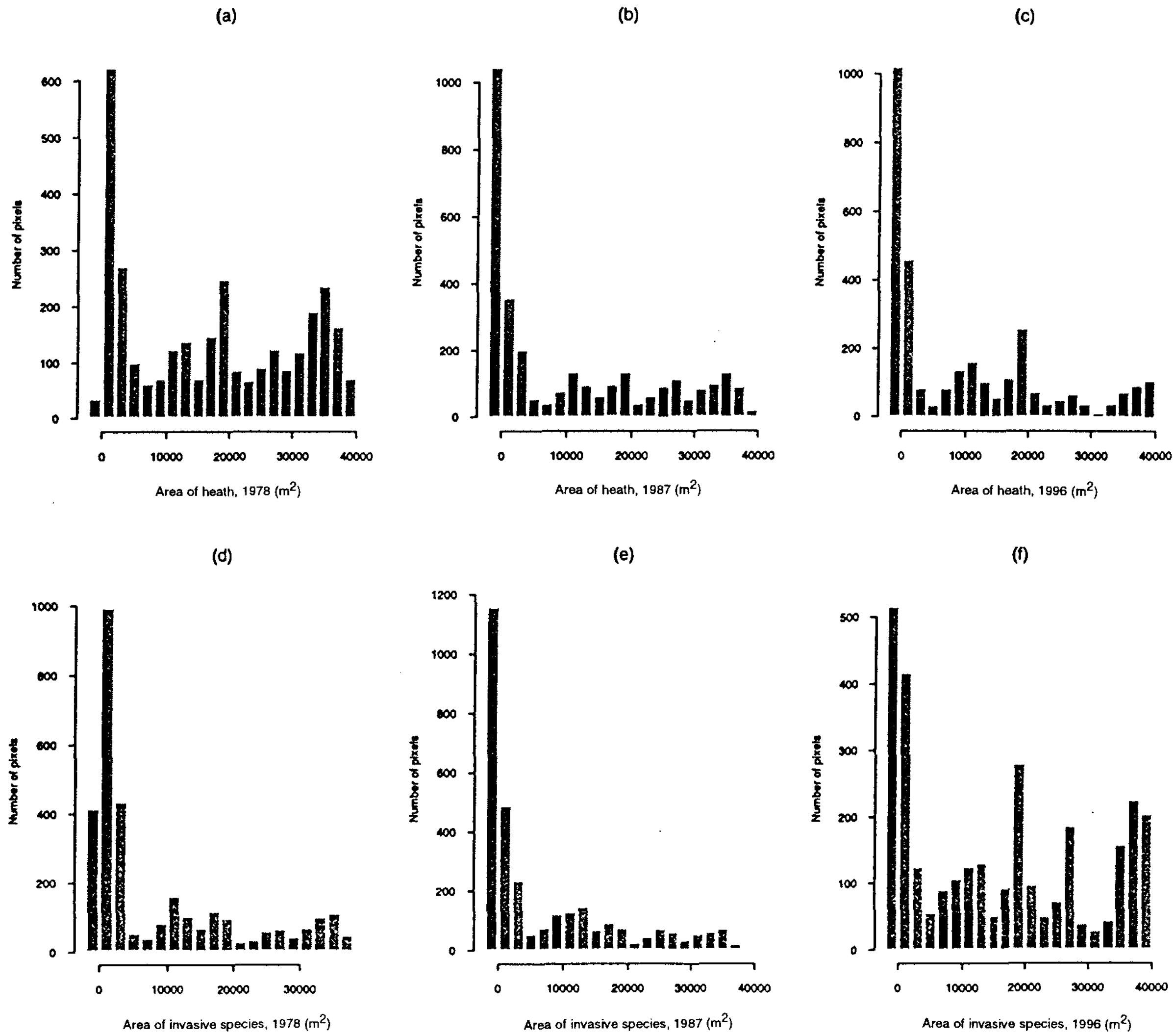


Fig. 5.1 Histograms of (a) the area of dwarf shrub vegetation in a pixel, 1978 (m^2); (b) the area of dwarf shrub vegetation in a pixel, 1987 (m^2); (c) the area of dwarf shrub vegetation in a pixel, 1996 (m^2); (d) the area of invasive species in a pixel, 1978 (m^2); (e) the area of invasive species in a pixel, 1987 (m^2); (f) the area of invasive species in a pixel, 1996 (m^2).

The histogram of area of invasive species in a pixel in 1978 was plotted (Fig. 5.1d). The majority of pixels contained a small area of invasive species (under 10,000 m^2). The frequency distribution of the areal extent of invasive species in 1987 was similar (Fig. 5.1e). However, in 1996 the distribution altered (Fig. 5.1f). The majority of pixels contained less than 10,000 m^2 of invasive species, but the number of pixels containing larger areas of invasive species rose considerably.

In summary, the area of dwarf shrub vegetation in a pixel tended to be small but there were a considerable number of pixels in 1978 which contained larger areas of dwarf shrub vegetation. In 1987 and 1996, the number of pixels containing larger areas of dwarf shrub vegetation fell. The area of invasive species in a pixel remained constant between 1978 and 1987 with most pixels containing a small area of invasive species. However, in 1996 the area of invasive species in a large number of pixels increased. Overall, percentage change in area of dwarf shrub vegetation in a pixel tended to be large with fewer small negative percentage changes.

5.4 Feature space plots

As in the per-patch analysis (Chapter 4, 4.5) percentage change in dwarf shrub vegetation, invasive species and 'others' in a pixel were plotted against each other.

Percentage change in invasive species was plotted against percentage change in area of dwarf shrub vegetation (Fig. 5.2a). The area of invasive species increased and the area of dwarf shrub vegetation decreased in many pixels. Of course, not all the decline in area of dwarf shrub vegetation was caused by invasive species. This was clear from the analysis of areal change over time (Chapter 4. 4.3). The points above the line in Figure 5.2a are those in which invasive species probably contributed to their decline. When percentage change in area of 'others' was plotted against percentage change in area of invasive species the result was as anticipated (Fig. 5.2b). Percentage change in area of 'others' appeared to cause little change in area of invasive species and *vice versa*. Finally, percentage change in area of 'others' was plotted against percentage change in area of dwarf shrub vegetation (Fig. 5.2c). Much of the decline in dwarf shrub vegetation appeared to be accounted for by increases in area of 'others'.

The analysis was repeated for percentage change in each aggregated primary category between 1987 and 1996. Initially, percentage change in area of invasive species was plotted against percentage change in area of dwarf shrub vegetation (Fig. 5.2d). It seemed that as the area of dwarf shrub vegetation decreased, the area of invasive species increased. Percentage change in area of 'others' was plotted against percentage change in area of invasive species (Fig. 5.2e). Again, percentage change in area of both 'others' and invasive species had little

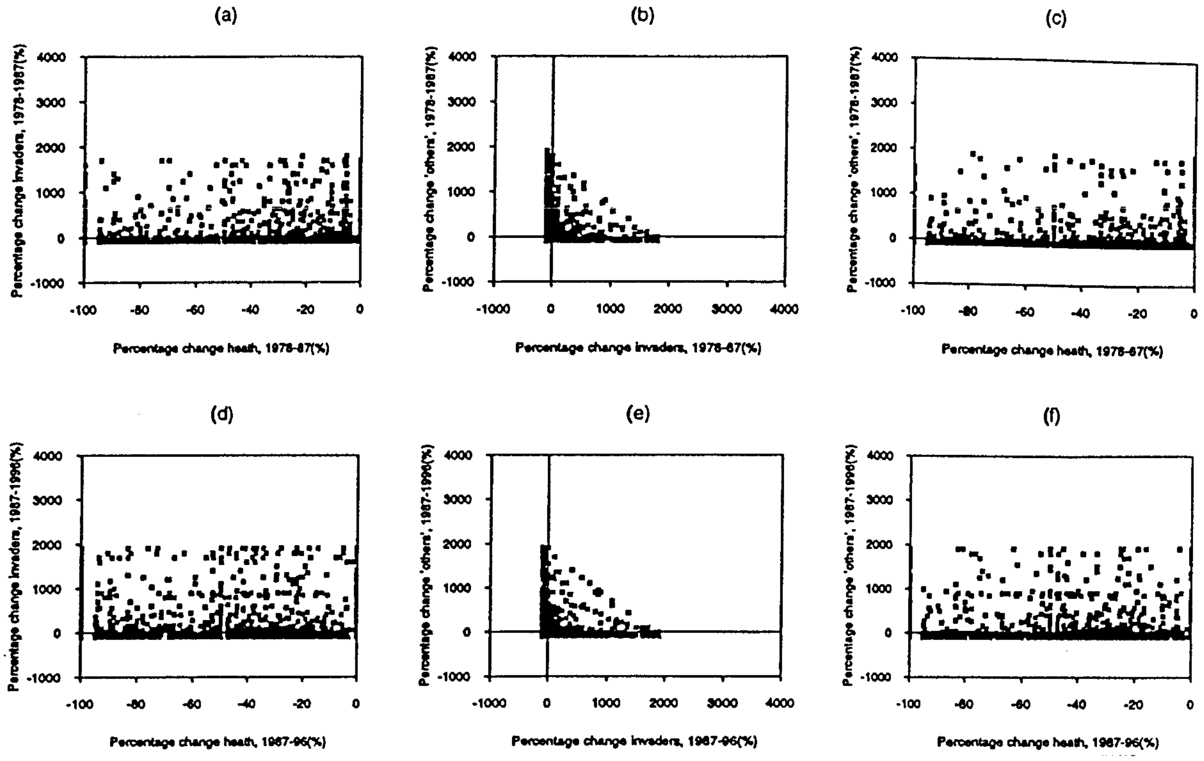


Fig. 5.2 Feature space plots of (a and d) percentage change in area of invasive species against percentage change in area of dwarf shrub vegetation (%); (b and e) percentage change in area of 'others' against percentage change in area of invasive species (%); (c and f) percentage change in area of 'others' against percentage change in area of dwarf shrub vegetation (%).

effect on each other. Finally, percentage change in area of 'others' was plotted against percentage change in area of dwarf shrub vegetation (Fig. 5.2f). The plot indicated that changes in land use caused change in area of invasive species.

In all, the feature space plots provided little insight into the mechanism of percentage change in area of dwarf shrub vegetation because of the large number of data plotted.

5.5 Mapping change

The data were considered in a spatial context with the aim of identifying spatial trends. By mapping change, change could be examined as part of a functioning landscape.

5.5.1 Mapping change between 1978 and 1987

Percentage change in area of dwarf shrub vegetation between 1978 and 1987 was mapped on a pixel basis (Fig. 5.3). Although the area of dwarf shrub vegetation declined in many pixels, it was obvious that change was not uniform across the landscape. Using alternate thresholds (see Chapter 4, 4.6.1) produced a similar map (Fig. 5.4), although there was an increase in the number of pixels remapped as 'unchanged'. Again, there was no spatial structure to this change.

5.5.2 Mapping change between 1987 and 1996

Percentage change in area of dwarf shrub vegetation between 1987 and 1996 was mapped on a pixel basis (Fig. 5.5). Again, there was no spatial structure to the change. The alternative thresholds were applied but the result was similar (Fig. 5.6). The area of dwarf shrub vegetation declined in most pixels but change was not uniform across Dorset.

5.5.3 Mapping change in the remaining aggregated primary categories

Change in the area of invasive species between 1978 and 1987 was mapped (Fig. 5.7). Again, there was no apparent spatial structure to the change. When change between 1987 and 1996 was mapped (Fig. 5.8) the outcome was similar.

Similarly, when change in area of 'others' between 1978 and 1987 was mapped (Fig. 5.9) there was no discernible structure to the pattern of change. Percentage change in area of 'others' between 1987 and 1996 (Fig. 5.10) was similar, that is percentage change was not uniform across Dorset.

5.5.4 Mapping change in selected primary categories

The primary categories which changed most between 1978 and 1987, and between 1987 and 1996 (see Chapter 4, 4.3) were mapped (Figs. 5.11 - 5.16). First, the area of grassland in a pixel between 1978 and 1987 was mapped (Fig. 5.11). Many pixels remained unchanged (1,951) as very few pixels contained grassland. Of the pixels which did contain some grassland, change was not uniform. The map of change between 1987 and 1996 was similar (Fig. 5.12). There was no structure to change in pixels which contained grassland.

Second, change in the areal extent of agriculture between 1978 and 1987 was mapped (Fig. 5.13). Again, the majority of pixels did not contain areas of agriculture (2,596), and of those which did, change was not uniform. Change between 1987 and 1996 was mapped (Fig. 5.14). Again, the majority of pixels did not contain agriculture. The area of agriculture decreased in the vast majority of pixels but there was no structure to the change.

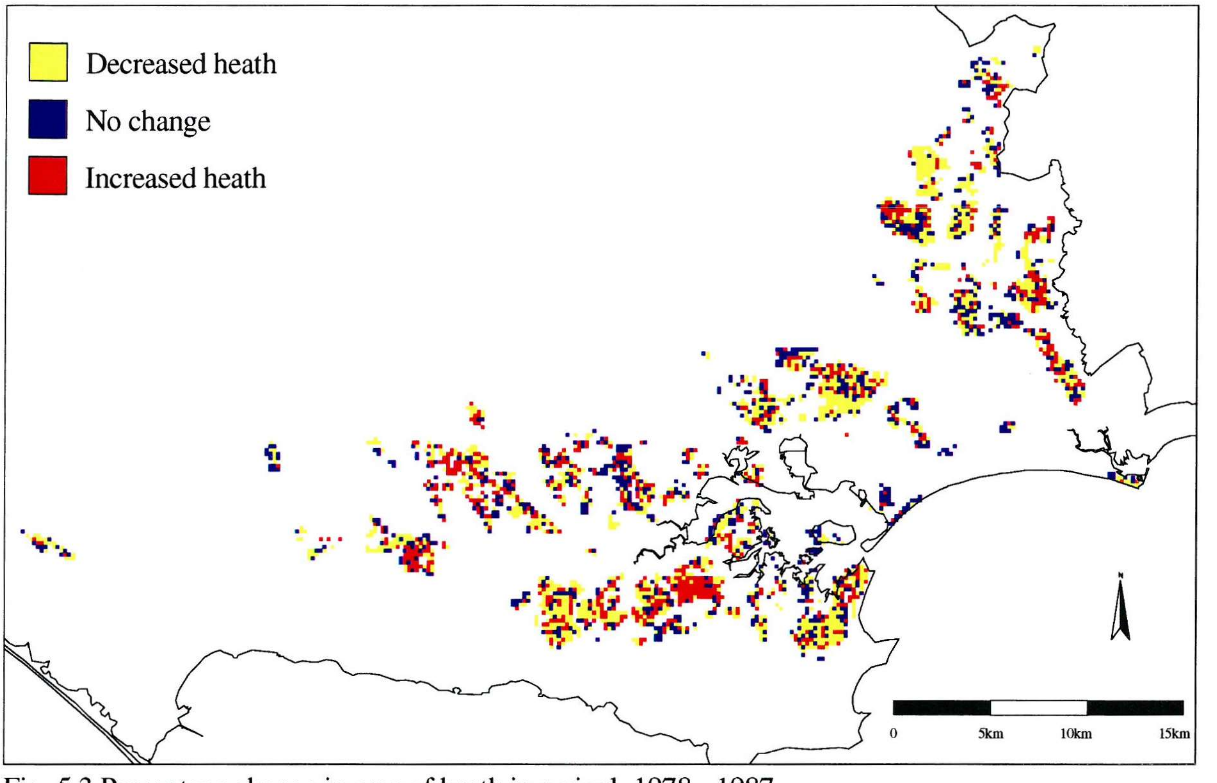


Fig. 5.3 Percentage change in area of heath in a pixel, 1978 –1987

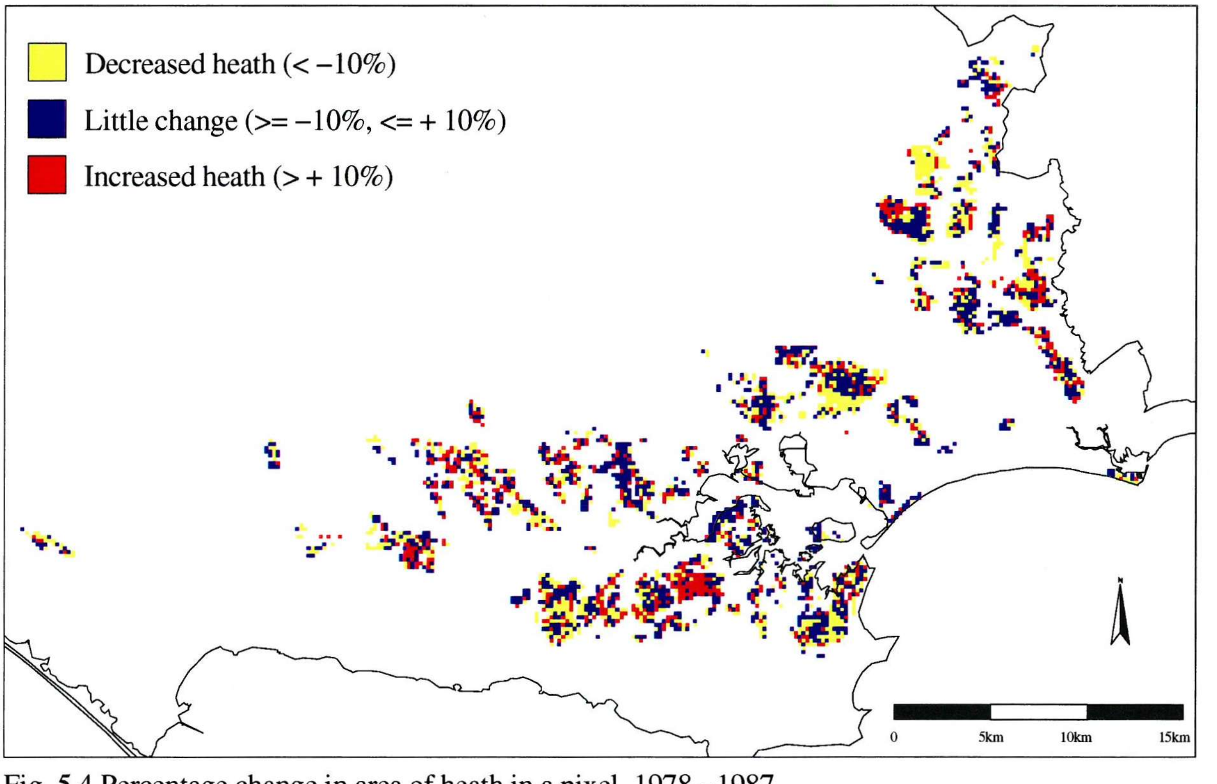


Fig. 5.4 Percentage change in area of heath in a pixel, 1978 –1987

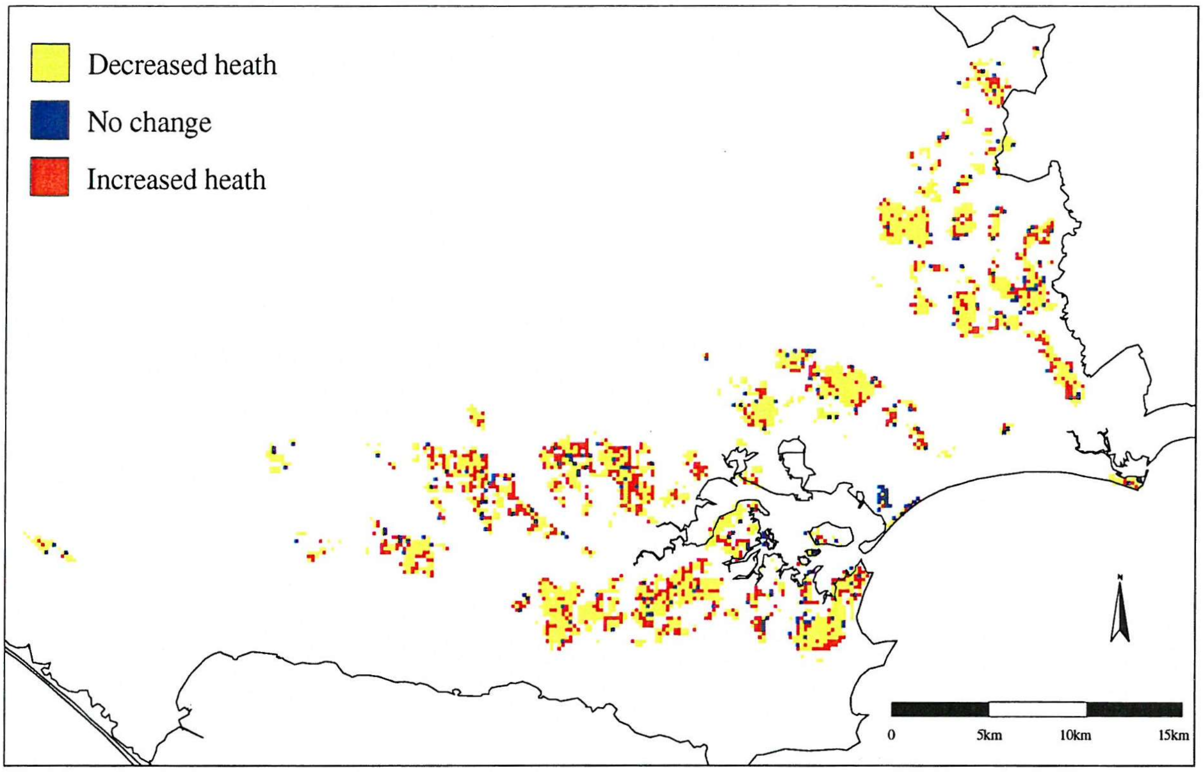


Fig. 5.5 Percentage change in area of heath in a pixel, 1987 –1996

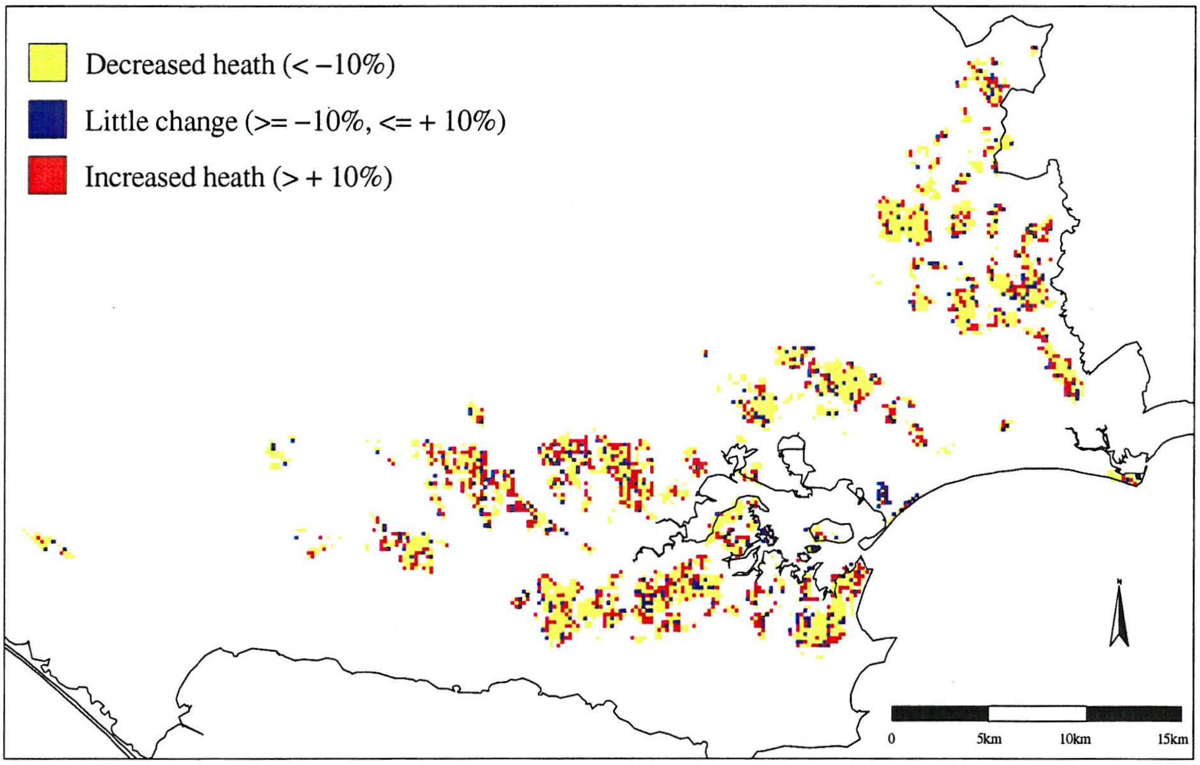


Fig. 5.6 Percentage change in area of heath in a pixel, 1987 –1996

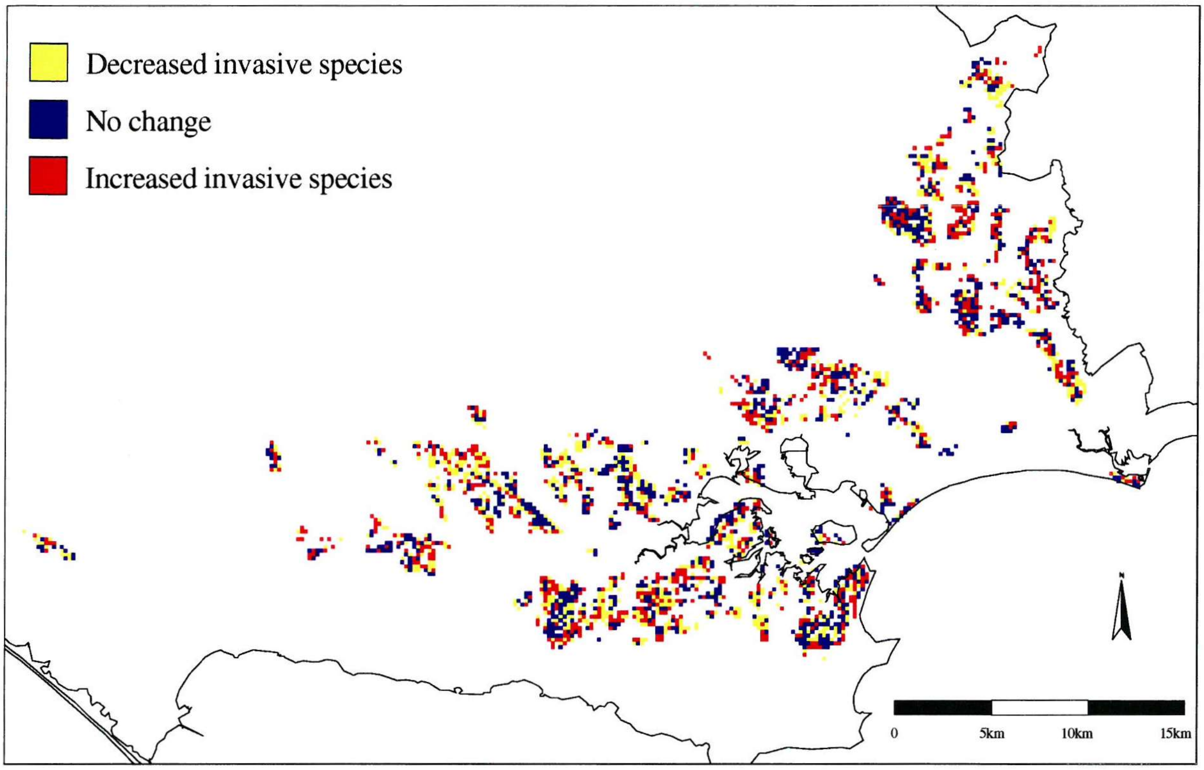


Fig. 5.7 Percentage change in area of invasive species in a pixel, 1978 –1987

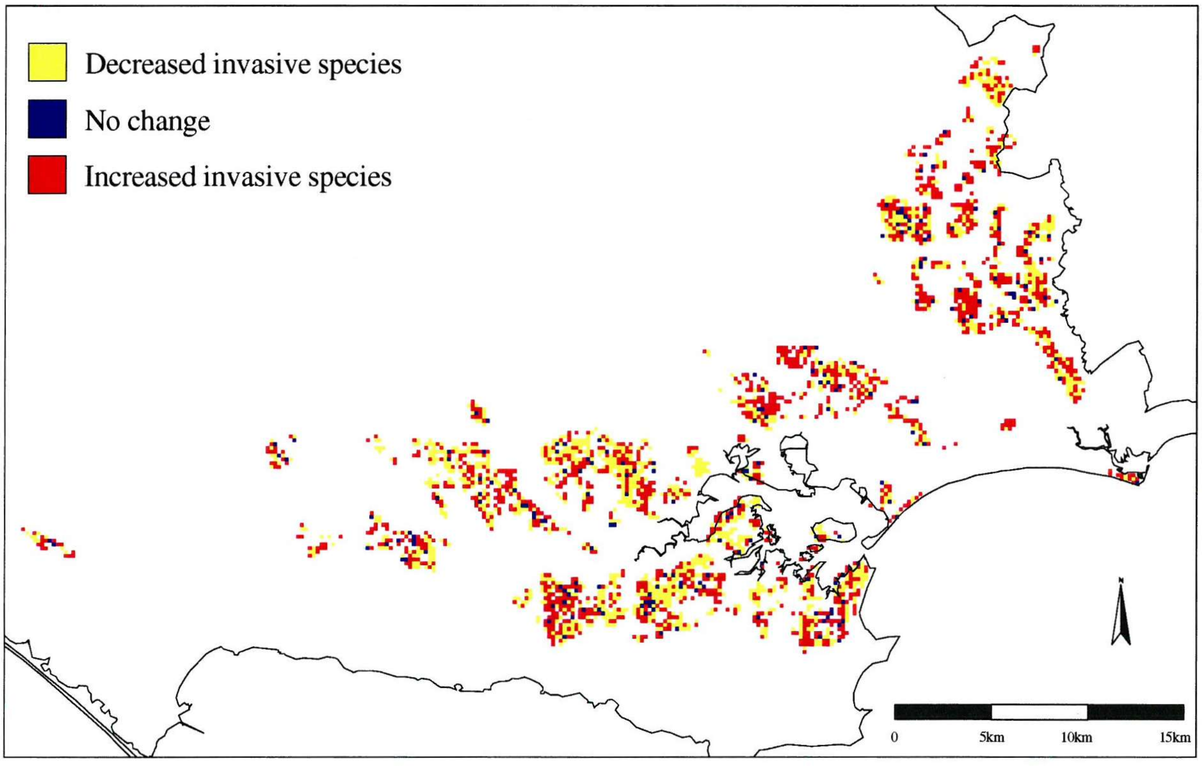


Fig. 5.8 Percentage change in area of invasive species in a pixel, 1987 –1996

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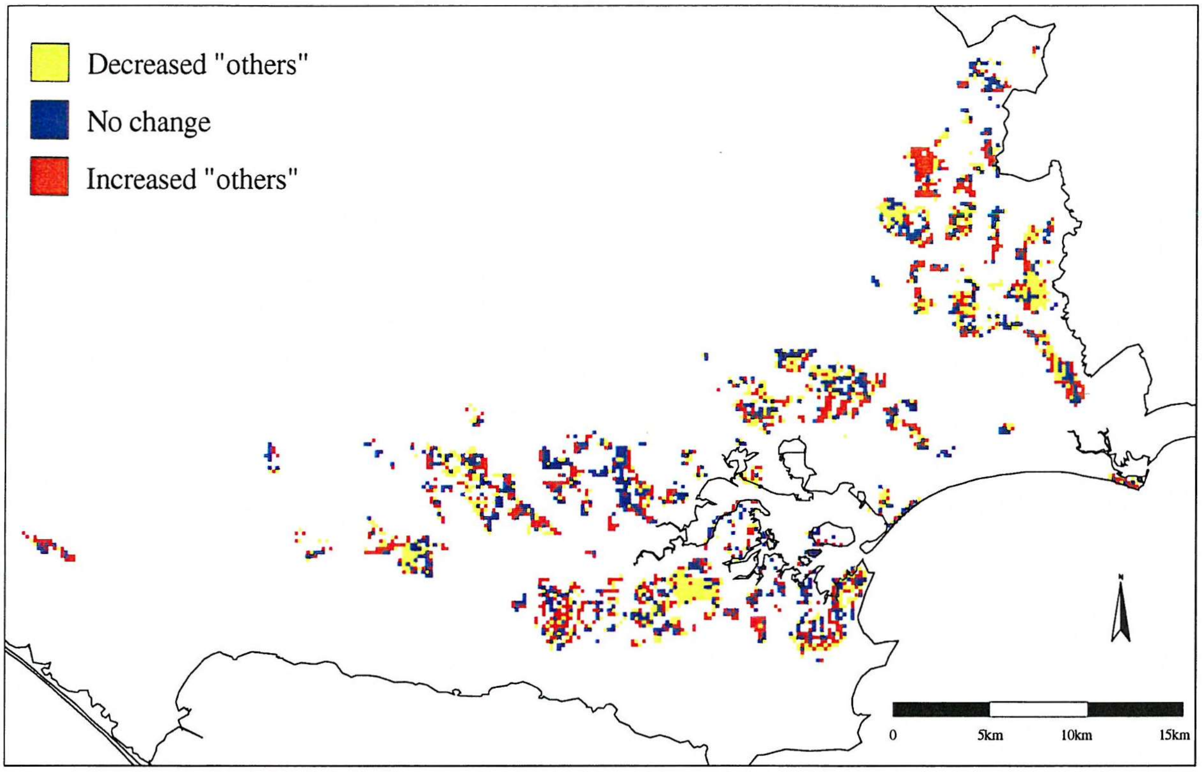


Fig. 5.9 Percentage change in area of "others" in a pixel, 1978 –1987

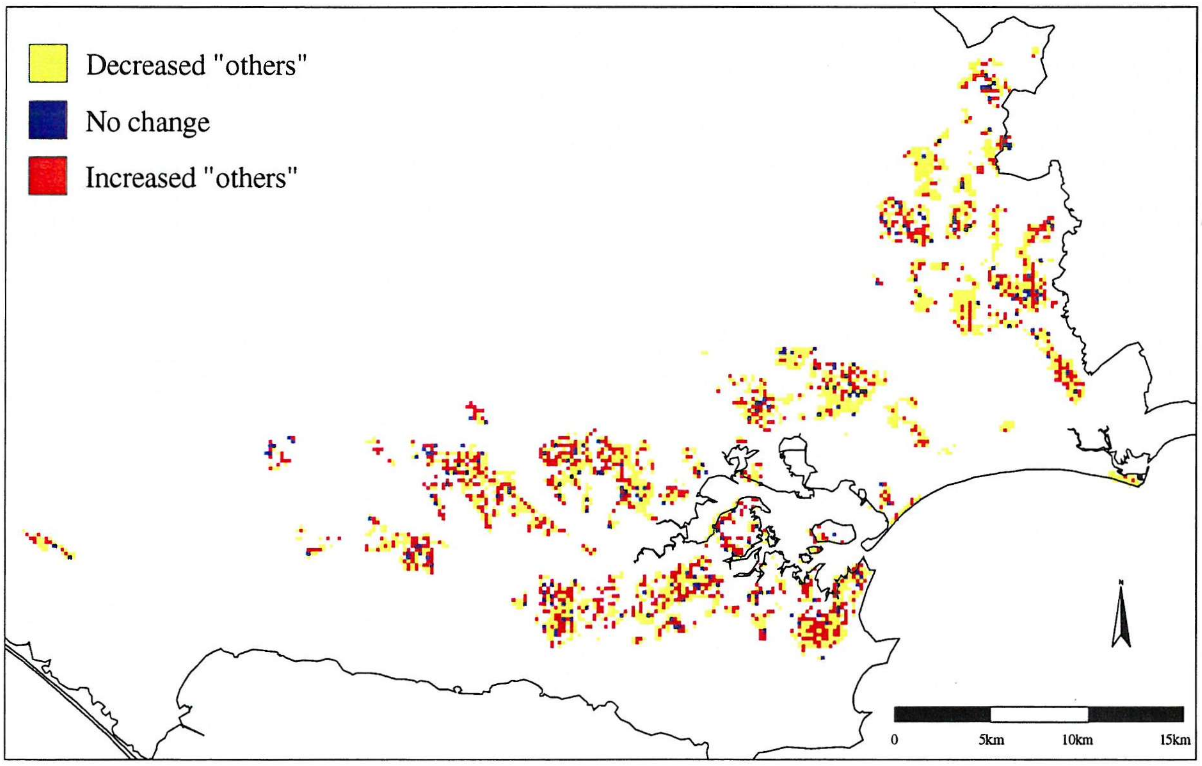


Fig. 5.10 Percentage change in area of "others" in a pixel, 1987 –1996

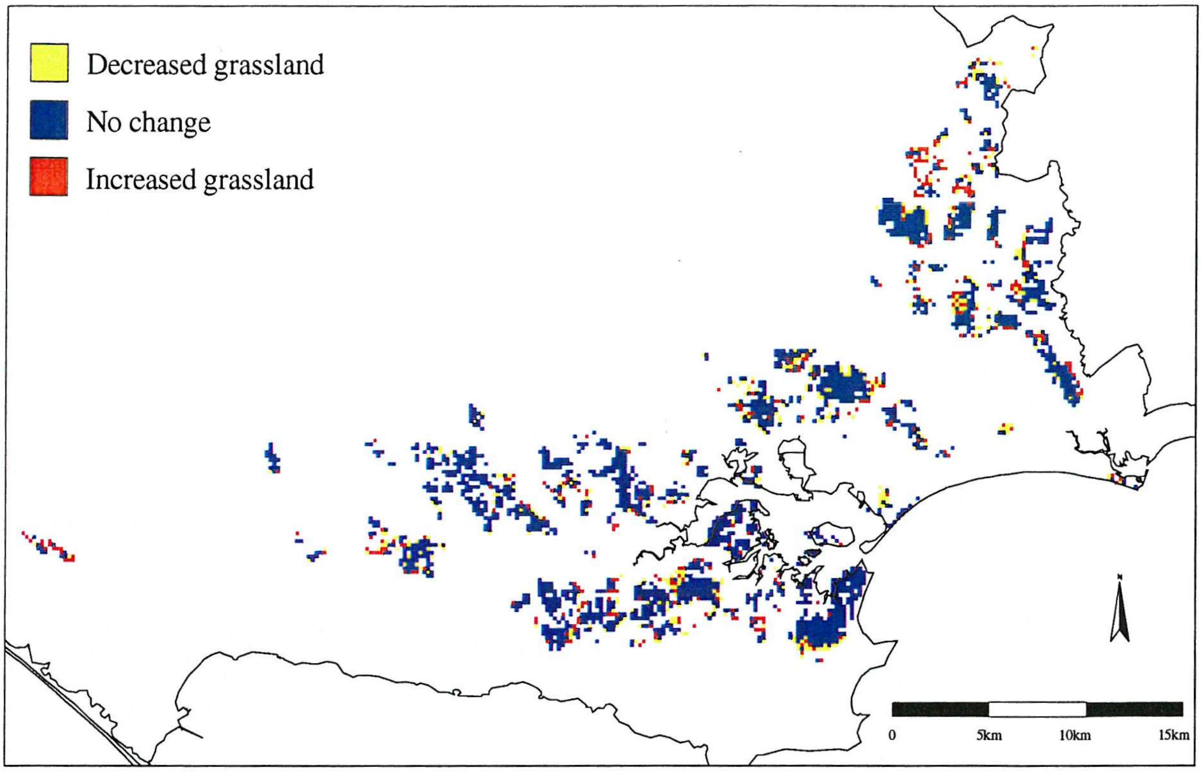


Fig. 5.11 Percentage change in area of grassland in a pixel, 1978 –1987

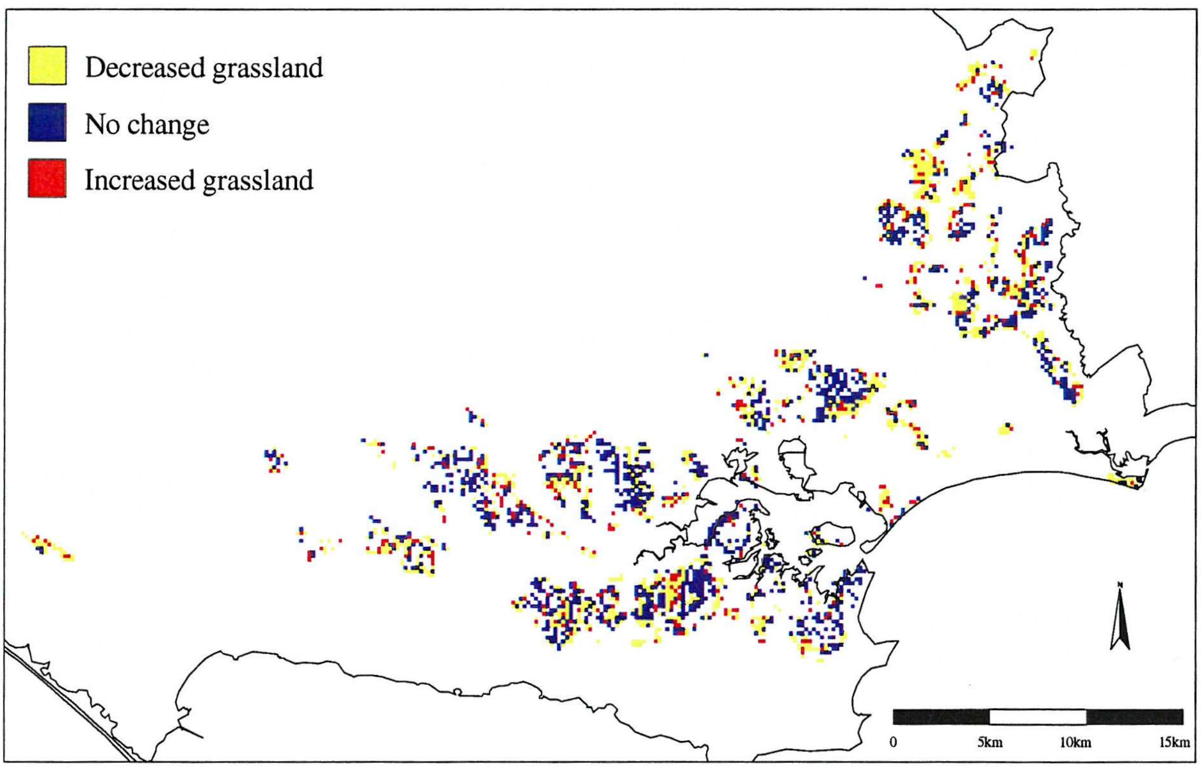


Fig. 5.12 Percentage change in area of grassland in a pixel, 1987 –1996

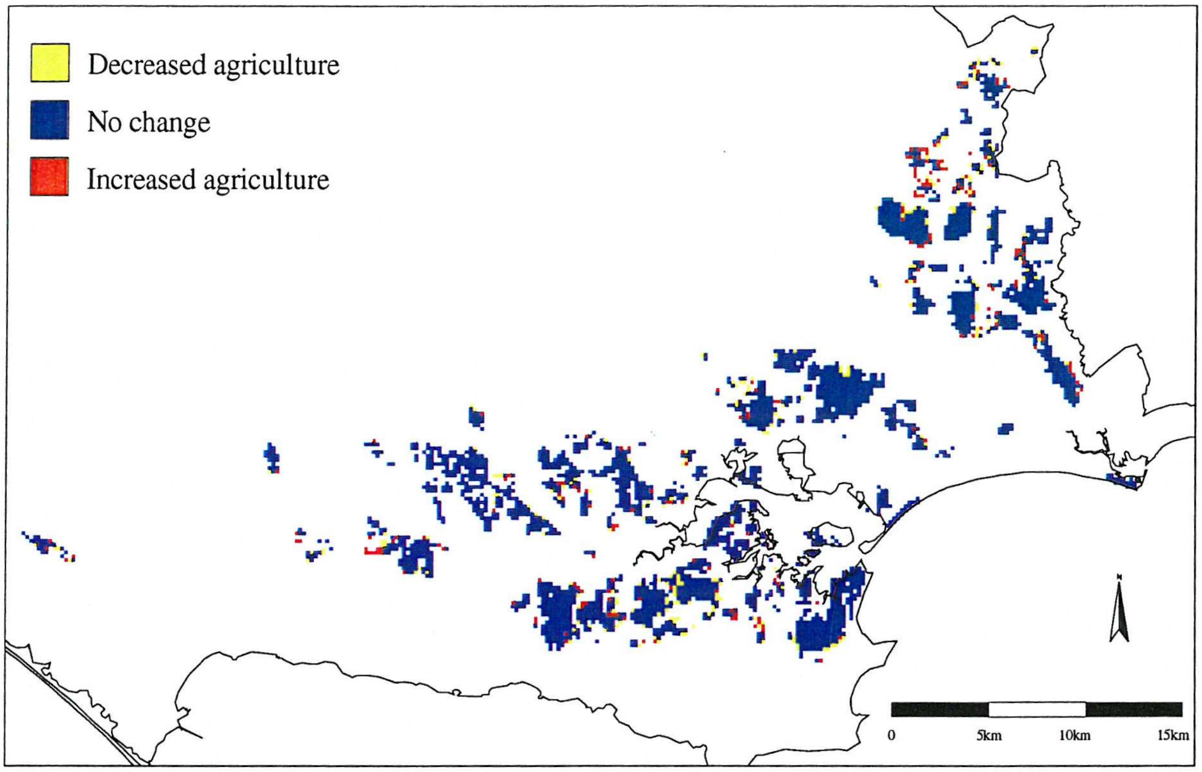


Fig. 5.13 Percentage change in area of agriculture in a pixel, 1978 –1987

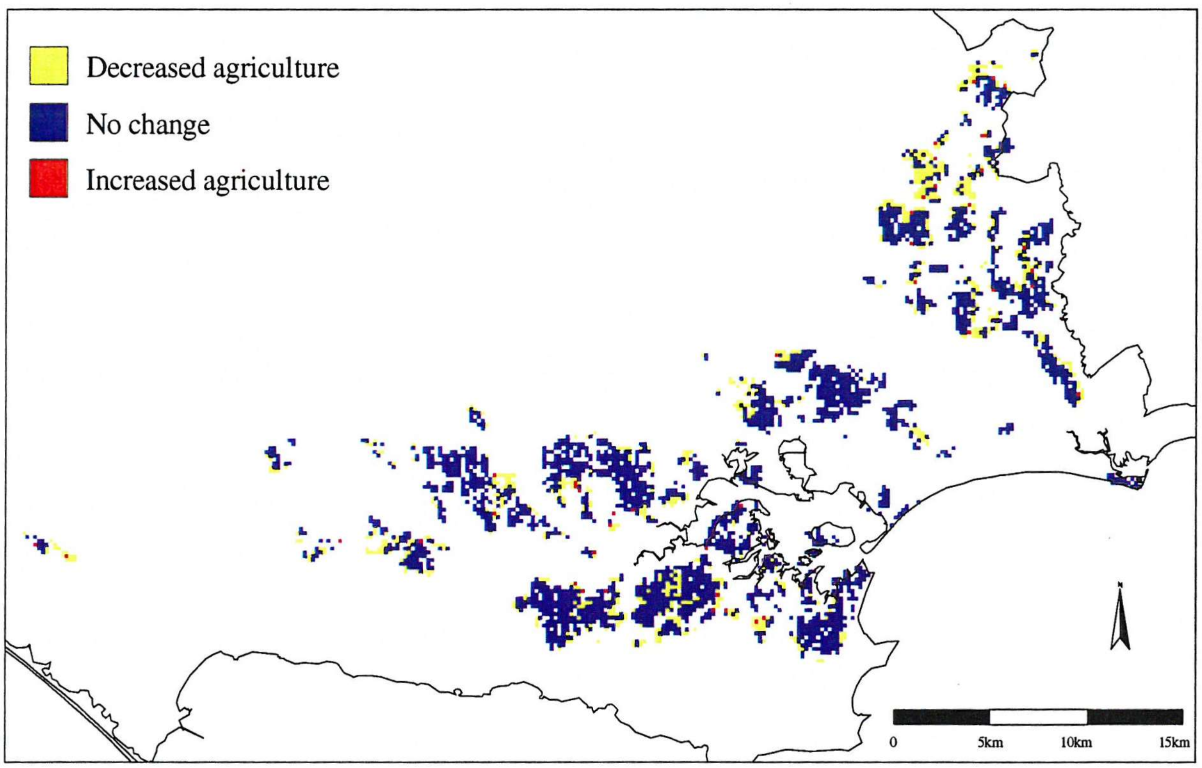


Fig. 5.14 Percentage change in area of agriculture in a pixel, 1987 –1996

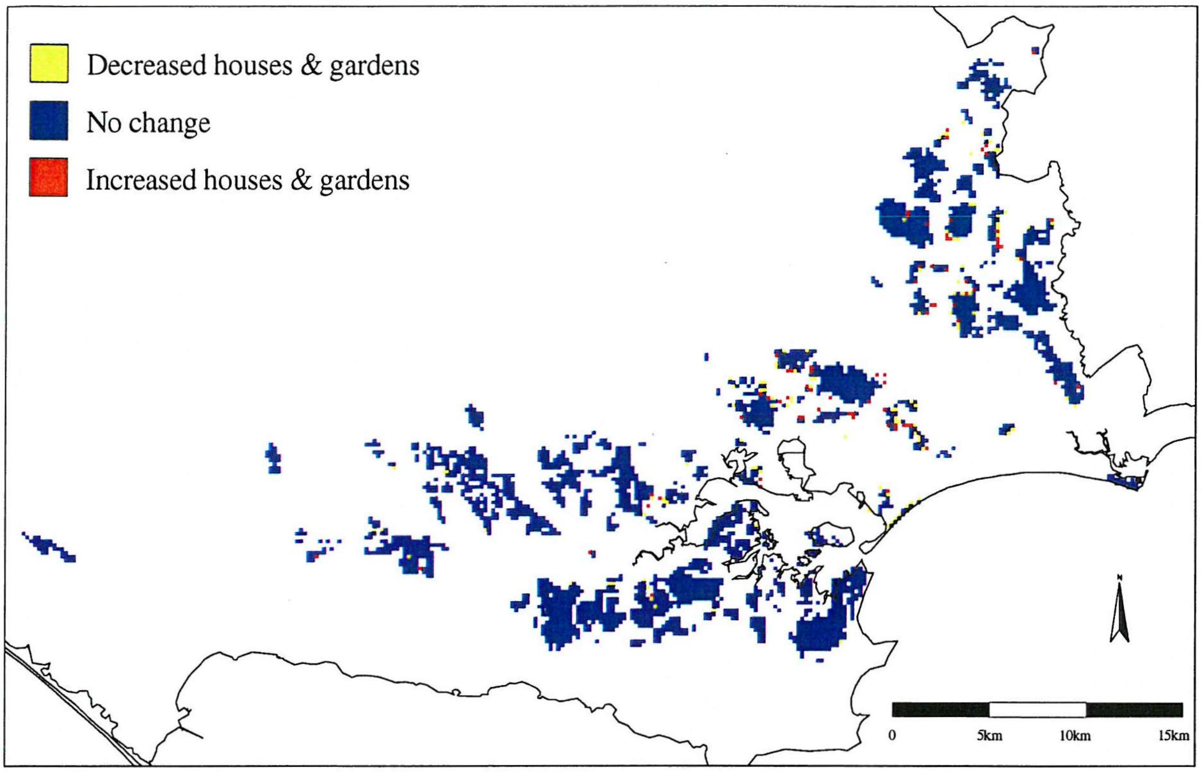


Fig. 5.15 Percentage change in area of houses and gardens in a pixel, 1978 –1987

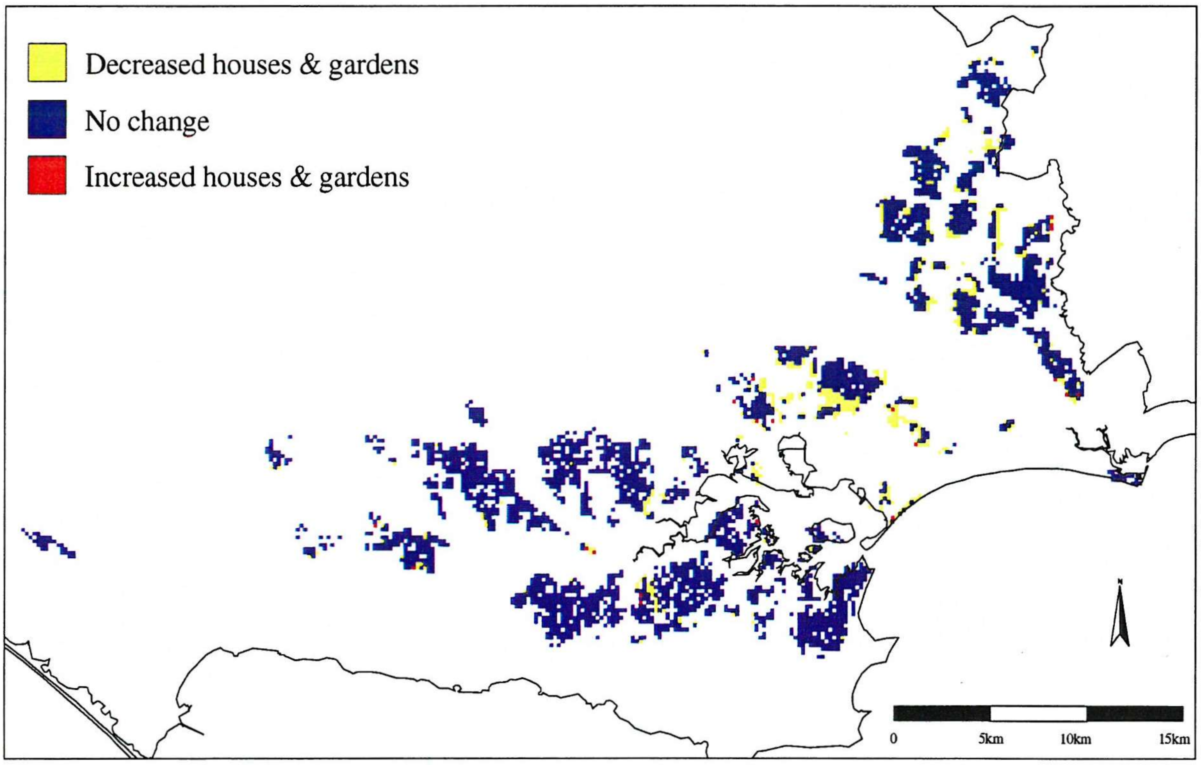


Fig. 5.16 Percentage change in area of houses and gardens in a pixel, 1987 –1996

Finally, change in the area of houses and gardens between 1978 and 1987 was mapped (Fig. 5.15). The majority of pixels did not contain any houses or gardens (2,831). There was no discernible structure to change in the pixels which did contain houses and gardens. The map of change between 1987 and 1996 (Fig. 5.16) was similar.

Mapping change was an attempt to investigate temporal change spatially. It was clear that there was no spatial structure to the temporal change irrespective of whether change was mapped at the aggregated primary category level, or the primary category level.

5.6 Bivariate analysis of change on a pixel-basis

Simple regression was carried out at the aggregated primary, primary and secondary category levels. It was anticipated that simple regression would indicate which explanatory variables best accounted for percentage change. The explanatory variables chosen for model building were based upon variation in ecological processes in dwarf shrub vegetation described in Chapter 2 (section 2.4.1) and were similar to those explanatory variables used during the patch-based analyses of change (Chapter 3, Table 3.6) with the exception of those variables which described the density of vegetation and the geometry of a patch (see Chapter 3, Table 3.7 for an example of the explanatory variables used for the pixel-based analysis). Further, as in the per-patch analysis, explanatory variables based on land use change and the relationship between dwarf shrub vegetation types were included in the analysis, although it had not been hypothesised that percentage change would be related with these variables as the analysis was concerned with natural change. Multiple regression analysis followed the simple regression analysis.

5.6.1 In general

As for the patch-based regression analysis (Chapter 4, 4.6.1) it was necessary to ensure approximately linear bivariate relations between percentage change and each of the explanatory variables. To examine the linearity of the relationships between percentage change in area of dwarf shrub vegetation between 1978 and 1987 (the response variable) and the explanatory variables, bivariate distribution functions (scatterplots) were plotted. For example, when percentage change in area of dwarf shrub vegetation between 1978 and 1987 was plotted against the area of dwarf shrub vegetation in a pixel (Fig. 5.17) it was evident that the relationship was not linear. Each x-axis variable was transformed in several ways (Chapter 4, Table 4.5) to ensure that each relation could be best approximated with a linear model. As in the patch-based analysis, the relation which was most linear resulted when both axes were logged.

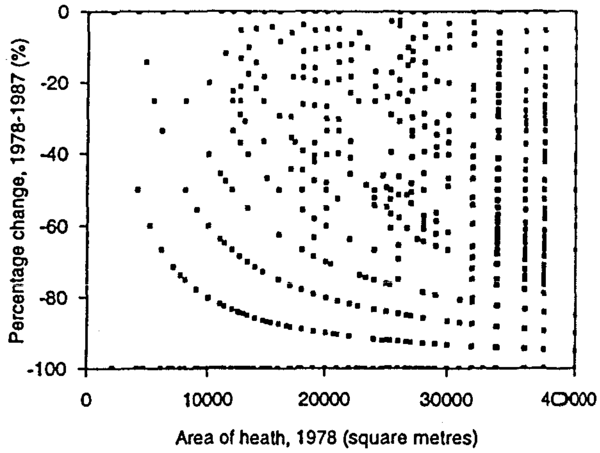


Fig. 5.17 Scatterplot of percentage change in area of dwarf shrub vegetation in a pixel, 1978-1987 against the area of dwarf shrub vegetation in a pixel, 1978 (m^2).

5.6.2 Regression for the aggregated primary categories, 1978-1987

Simple regression was carried out to examine what relationship, if any, existed between percentage change in area of dwarf shrub vegetation and each explanatory variable (Table 5.1). A confidence interval of 95% was used. Therefore, there was a 1:20 chance of a Type I error, that is an erroneous rejection of the null hypothesis (H_o).

5.6.2.1 Simple regression for the aggregated primary categories, 1978 - 1987

Only one attribute accounted for a significant amount of variation in percentage change in area of dwarf shrub vegetation between 1978 and 1987 (Table 5.2). Percentage change was significantly correlated with area of dwarf shrub vegetation ($r^2 = 0.08$). The area of dwarf shrub vegetation in a pixel was inversely related with percentage change which was the converse of the hypothesised relationship (Ho) (Fig. 5.18). As the area of dwarf shrub vegetation in a pixel increased, so did percentage change. Multiple regression was not carried out because of the small coefficient of determination and because the single significant relationship was not as hypothesised.

Table 5.2. Simple regression for percentage change in area of heath versus pixel-based aggregated primary categories, 1978. Only the significant relationships are shown.

Logged, pixel-based, explanatory variables	*df*	*p*	r^2	Ho/H_1	**Relationship**
Area of heath in a pixel	1,2244	0	0.08	H_0	Negative

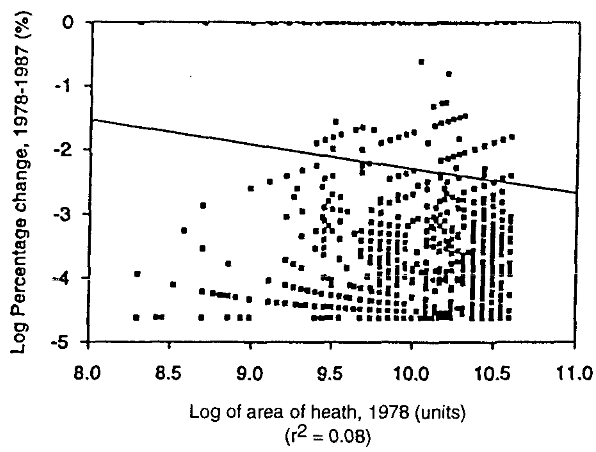


Fig. 5.18 Scatterplot of log percentage change in area of dwarf shrub vegetation in a pixel, 1978-1987 against log area of dwarf shrub vegetation in a pixel, 1978.

5.6.3 Regression for the aggregated primary categories, 1987 - 1996

Regression was carried out at the aggregated primary category level, followed by the primary and secondary category levels

5.6.3.1 Simple regression for the aggregated primary categories, 1987 - 1996

Simple regression resulted in two attributes accounted for significant amounts of variation in percentage change in area of dwarf shrub vegetation between 1987 and 1996 (Table 5.3). Area of dwarf shrub vegetation in a pixel was most highly correlated with percentage change (r^2 = 0.47). The inverse relationship was contrary to that hypothesised (Fig. 5.19a). The inverse relationship between percentage change and area of invasive species in a pixel was as hypothesised (Fig. 5.19b) (r^2 = 0.11).

Table 5.3. Simple regression for percentage change in area of heath versus pixel-based aggregated primary categories, 1987. Only the significant relationships are shown.

Logged, pixel-based, explanatory variables	*df*	*p*	r^2	Ho/H_1	**Relationship**
Area of heath in a pixel	1, 2537	0	0.47	H_0	Negative
Area of invasive species in a pixel	1, 2537	0	0.11	H_1	Negative

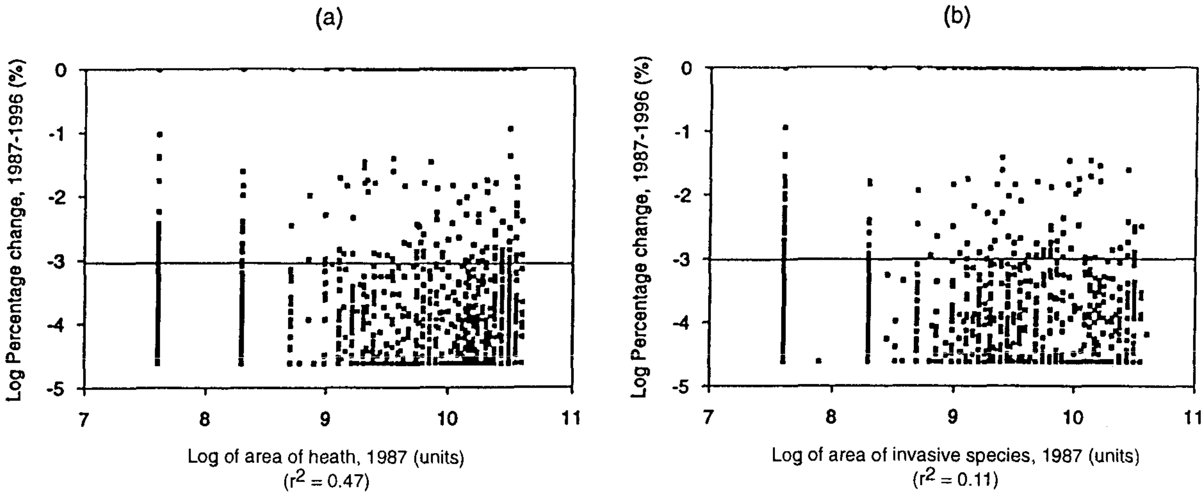


Fig. 5.19 Scatterplots of (a) log percentage change in area of dwarf shrub vegetation, 1987-1996 against log area of dwarf shrub vegetation in a pixel, 1987; (b) log percentage change in area of dwarf shrub vegetation, 1987-1996 against log area of invasive species in a pixel, 1987.

5.6.3.2 Multiple regression for the aggregated primary categories, 1987 - 1996

Percentage change in area of dwarf shrub vegetation between 1987 and 1996 was significantly correlated with area of dwarf shrub vegetation in a pixel ($r^2 = 0.47$), but the other explanatory variables could not adequately account for any variation in percentage change when the influence of area was held constant.

5.7 An alternative analysis

It became clear that the regression analysis outlined above was flawed. Based on current understanding of dwarf shrub vegetation dynamics in a fragmented environment, it was not reasonable that as area of dwarf shrub vegetation increased, percentage change increased. The inverse relationship continued when regression was carried out at the primary category level. In fact, the coefficients of determination increased. For example, area of wet heath accounted for 80% of the variation in percentage change in area of wet heath between 1987 and 1996. However, the relationship between percentage change and area remained negative. Therefore, the regression results indicated that something was not quite right, which led to an in-depth analysis of the data. The data were examined to isolate any likely causal factors of the highly correlated and negative relationship between percentage change and area.

The first step taken involved plotting the data. When the log of percentage change was plotted against the log of area of dwarf shrub vegetation in a pixel, it became clear that using a logarithmic transformation of the data caused problems. Smaller areas of dwarf shrub vegetation were less likely to decrease in area than their larger counterparts because vegetation was scored on a scale between zero and three. An area of dwarf shrub vegetation of 2,000 m^2, the smallest area possible, could only remain unaltered or decrease by 100% (as increases were not included in the regression analysis). The small areas of dwarf shrub vegetation could only remain unchanged or disappear completely where other areas (for example, from 4,000 m^2 to 40,000 m^2) had the freedom to change.

There were many small areas of dwarf shrub vegetation which could only change by 0% or 100%. When such data were log transformed they remained unaltered. However, when the other, larger areas of dwarf shrub vegetation were log transformed the mean varied as it had the freedom to change. This led to bias in the regression relations causing the large coefficients of determination. Further, the initial premise of the first Dorset Heathland Survey was that only pixels containing dwarf shrub vegetation were to be surveyed. Over time (for example, in 1987), it was likely that at least a small area of the dwarf shrub vegetation originally surveyed would remain. As dwarf shrub vegetation was being surveyed, the remaining area, irrespective of size, would be recorded. Therefore, the surveys in 1987 and 1996 may have been biased.

These two notions gave rise to an investigation of the data. Area of dwarf shrub vegetation in 1978, 1987 and 1996 was grouped into areas of varying size and percentage change in each of the groups examined (Table 5.4). It was clear that the suspected bias appeared to be true. The smallest areas of dwarf shrub vegetation were less likely to decline as the majority of pixels contained smaller areas of dwarf shrub vegetation.

Table 5.4 Percentage change in pixels containing various areas of dwarf shrub vegetation in 1978.

Area of dwarf shrub vegetation in a pixel (m^2)	**Percentage decrease (%)**
0 - 3,000 m^2	18
3,000 - 5,000 m^2	91
5,000 - 10,000 m^2	54
10,000 - 40,000 m^2	75

The analysis was repeated for the 1987 data (Table 5.5). However, smaller areas were inclined to change as much as middle sized areas, although larger areas of dwarf shrub vegetation changed considerably more than their smaller counterparts. Although there appeared to be little bias in the data, the problems caused by log transforming the smallest areas of dwarf shrub vegetation remained (such data could only change by 0% or 100% and, therefore, did not have the freedom to change when logged). To remove the effect of the logarithmic transformation of the data any pixels containing an area of dwarf shrub vegetation of 3,000 m^2 or less in in 1978 and 1987 were removed and the regression analysis repeated. A threshold of 3,000 m^2 was used to isolate pixels with 2,000 m^2 which introduced the bias. This ensured the regressions were consistent throughout the analysis.

Table 5.5 Percentage change in pixels containing various areas of dwarf shrub vegetation in 1987.

Area of dwarf shrub vegetation in a pixel (m^2)	Percentage decrease (%)
0 - 3,000 m^2	45
3,000 - 5,000 m^2	49
5,000 - 10,000 m^2	44
10,000 - 40,000 m^2	71

5.7.1 Regression for the aggregated primary categories, 1978 - 1987

Simple regression was carried out using the new data, with the areas of less than 3,000 m^2 removed. In all cases, both axes were log transformed. As a large number of data were analysed (in excess of 1,700 pixels on occasion) at the 95% confidence interval, a coefficient of determination in excess of 0.02 was statistically significant (because of the large number of data: Webster & Oliver, (1990) pp 82). Although such a small coefficient of determination was statistically significant, in reality it could not be used for predictive purposes. Regression analysis was carried out at the aggregated primary category level, followed by the primary and secondary category levels.

5.7.1.1 Simple regression for the aggregated primary categories, 1978 - 1987

Percentage change in area of dwarf shrub vegetation between 1978 and 1987 was correlated with a single variable. The area of dwarf shrub vegetation in a pixel accounted for 2% of the variation in percentage change (Table 5.6). The inverse relationship was not as hypothesised: as area increased, percentage change increased (Fig. 5.20). Again, the relationship was not in the hypothesised direction, despite the bias having been removed. Multiple regression was not carried out as a result of the small coefficients of determination.

Table 5.6. Simple regression for percentage change in area of dwarf shrub vegetation versus pixel-based aggregated primary categories, 1978.

Logged, pixel-based, explanatory variables	*df*	*p*	r^2	Ho/H_1	Relationship
Area of heath in a pixel	1, 1779	2.8e-10	0.02	H_0	Negative

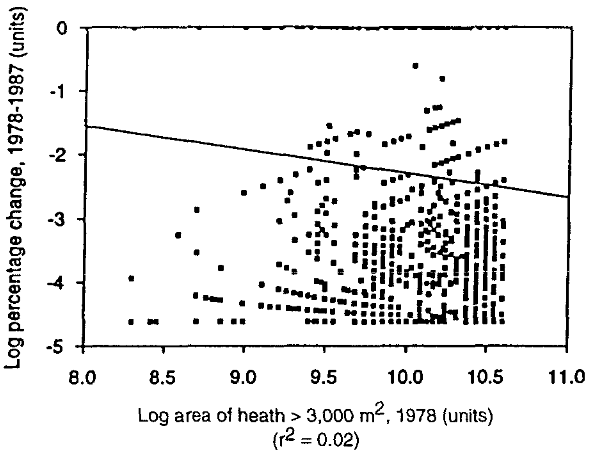


Fig. 5.20 Scatterplot of log percentage change in area of dwarf shrub vegetation, 1978-1987 against log area of dwarf shrub vegetation (> 3,000 m^2) in a pixel, 1978.

5.7.2 Regression for the primary categories, 1978 - 1987

Simple regression was carried out at the aggregated primary category level in 1978 with the aim of accounting for percentage change in area of dry heath, humid heath, wet heath and peatland in turn.

5.7.2.1 Simple regression for area of dry heath, 1978 - 1987

Simple regression resulted in two variables accounting for some variation in percentage change in area of dry heath between 1978 and 1987 (Table 5.8). Area of dry heath in a pixel and distance each accounted for 2% of the variation in percentage change. As hypothesised, both were positively related with percentage change (Fig. 5.21a and Fig. 5.21b). The relationships indicated that greater areas of dry heath in a pixel are less susceptible to change than smaller areas. Also, pixels towards the centre of a cluster are less easily invaded, probably because such pixels tend to be surrounded by a greater area of dwarf shrub vegetation. As in the aggregated primary category analysis, the coefficients of determination remained small and, therefore, multiple regression was not carried out. However, the relationships were in the right direction.

Table 5.8. Simple regression for percentage change in area of dry heath versus pixel-based aggregated primary categories, 1978.

Logged, pixel-based, explanatory variables	*df*	*p*	r^2	Ho/H_1	**Relationship**
Area of dry heath in a pixel	1, 973	3.3e-06	0.02	H_1	Positive
Distance from edge	1, 973	7.0e-06	0.02	H_1	Positive

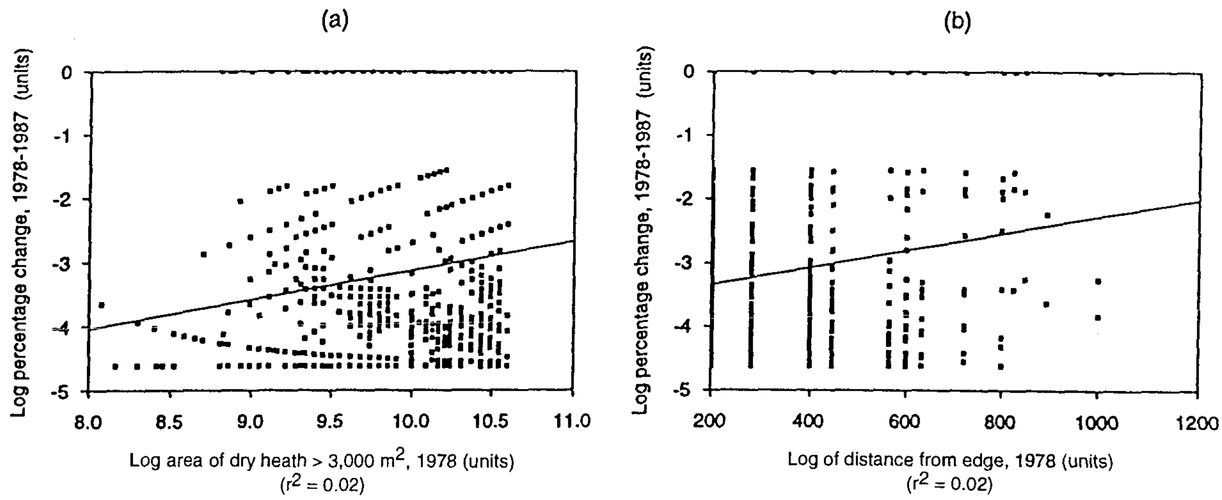


Fig. 5.21 Scatterplots of (a) log percentage change in area of dry heath, 1978-1987 against log area of dry heath (> 3,000 m^2) in a pixel, 1978; (b) log percentage change in area of dry heath, 1978-1987 against log distance from the edge, 1978.

5.7.2.2 Simple regression for area of wet heath, 1978 - 1987

No variable was significantly correlated with percentage change in area of wet heath between 1978 and 1987.

5.7.2.3 Simple regression for area of humid heath, 1978 - 1987

Percentage change in area of humid heath in a pixel was correlated with two variables (Table 5.9). The area of grassland in a pixel accounted for 2% of the variation in percentage change and the area of houses and gardens in a pixel accounted for 3% of the variation. Area of grassland was negatively related with percentage change (Fig. 5.22a), as was the area of houses and gardens in a pixel (Fig. 5.22b). That is, as area increased, percentage change increased. Neither relationship had been hypothesised simply because land use change is not readily predicted. Again, multiple regression was not carried out.

Table 5.9. Simple regression for percentage change in area of humid heath versus pixel-based aggregated primary categories, 1978.

Logged, pixel-based, explanatory variables	*df*	*p*	r^2	*Ho*/*H*1	**Relationship**
Area of grassland in a pixel	1, 563	0	0.02	-	Negative
Area of houses and gardens in a pixel	1, 563	0	0.03	-	Negative

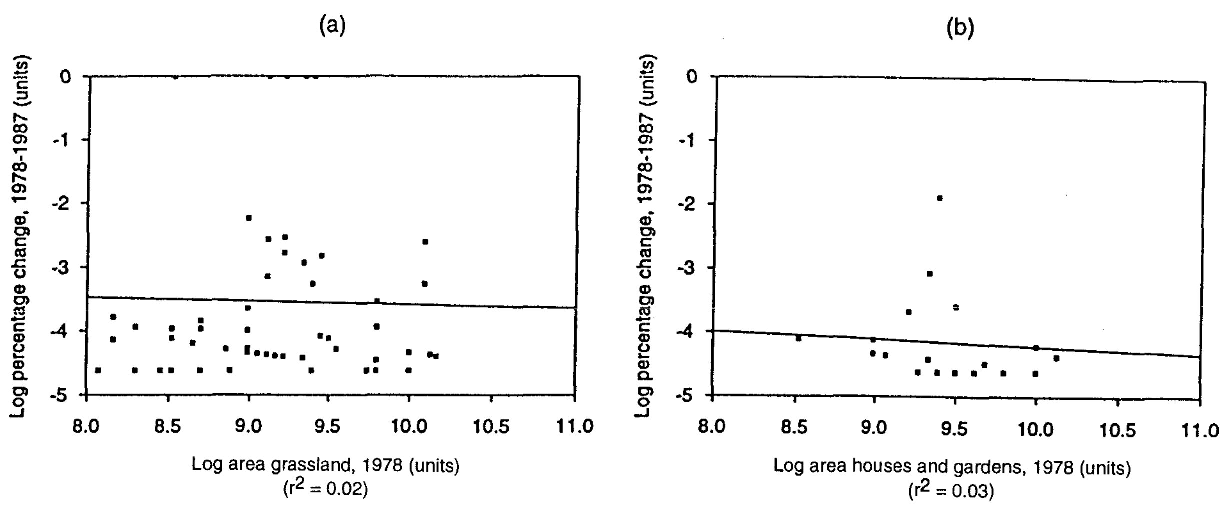


Fig. 5.22 Scatterplots of (a) log percentage change in area of humid heath, 1978-1987 against log area of grassland in a pixel in a pixel, 1978; (b) log percentage change in area of humid heath, 1978-1987 against log area of houses and gardens in a pixel, 1978.

5.7.2.4 Simple regression for area of peatland, 1978 - 1987

Simple regression resulted in six attributes accounting for some variation in percentage change in area of peatland between 1978 and 1987 (Table 5.10). As hypothesised, percentage change was positively correlated with the area of peatland in a pixel (r^2 = 0.02) (Fig. 5.23a). The relationship between percentage change and the remaining variables had not been hypothesised. Percentage change was inversely correlated with area of grassland (r^2 = 0.05) (Fig. 5.23b) and with area of agriculture in a pixel (r^2 = 0.04) (Fig. 5.23c). The ratio of area of peatland to wet heath, the ratio of area of peatland to humid heath and the ratio of area of peatland to dry heath in a pixel also accounted for some variation in percentage change. Percentage change was negatively correlated with the ratio of area of peatland to wet heath and the ratio of area of peatland to humid heath (Fig. 5.23d and Fig. 5.23e). As the area of peatland increased relative to both the area of wet heath and humid heath in a pixel, percentage change increased. Such relationships were the likely result of the influence of climatic factors on the various dwarf shrub vegetation types (see Chapter 4, 4.7.3.1). In contrast, the relationship between percentage change and the ratio of area of peatland to dry heath was positive (Fig. 5.23f). Percentage change decreased as the area of peatland relative to the area of dry heath increased. Again, multiple regression analysis was deemed unnecessary because of the small coefficients of determination.

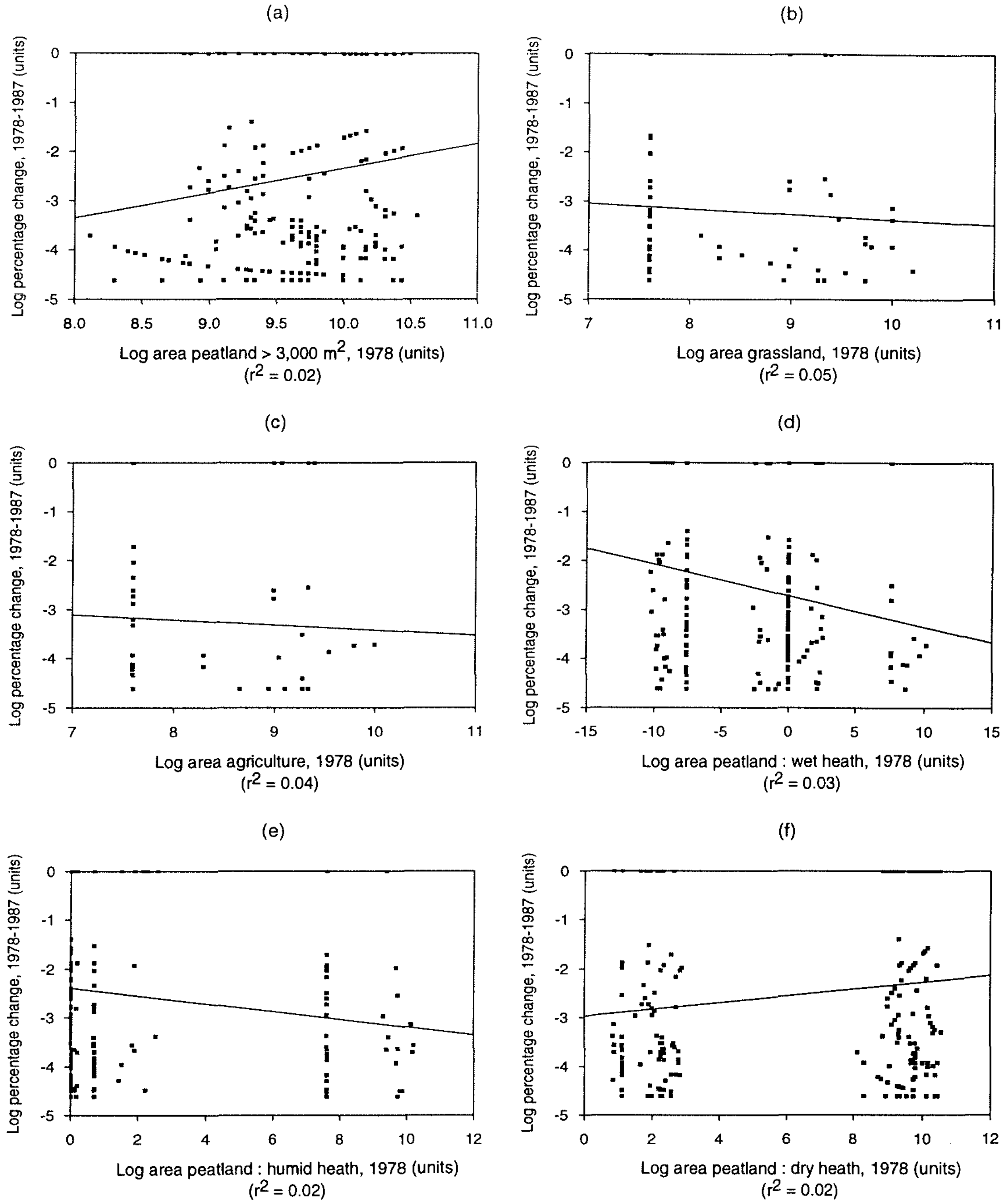


Fig. 5.23 Scatterplots of (a) log percentage change in area of peatland, 1978-1987 against log area of peatland (> 3,000 m^2) in a pixel, 1978; (b) log percentage change in area of peatland, 1978-1987 against log area of grassland in a pixel, 1978; (c) log percentage change in area of peatland, 1978-1987 against log area of agriculture in a pixel, 1978; (d) log percentage change in area of peatland, 1978-1987 against log ratio of area of peatland to wet heath in a pixel, 1978; (e) log percentage change in area of peatland, 1978-1987 against log ratio of area of peatland to humid heath in a pixel, 1978; (f) log percentage change in area of peatland, 1978-1987 against log ratio of area of peatland to dry heath in a pixel, 1978.

Table 5.10. Simple regression for percentage change in area of peatland versus pixel-based aggregated primary categories, 1978.

Logged, pixel-based, explanatory variables	*df*	*p*	r^2	Ho/H_1	Relationship
Area of peatland in a pixel	1, 237	0.023	0.02	H_1	Positive
Area of grassland in a pixel	1, 237	0.000	0.05	-	Negative
Area of agriculture in a pixel	1, 237	0.003	0.04	-	Negative
Area of peatland : wet heath in a pixel	1, 237	0.005	0.03	-	Negative
Area of peatland : humid heath in a pixel	1, 237	0.025	0.02	-	Negative
Area of peatland : dry heath in a pixel	1, 237	0.014	0.02	-	Positive

5.7.3 Regression for the aggregated primary categories, 1987 - 1996

Regression analysis was carried out at the aggregated primary category level, followed by the primary and secondary category levels.

5.7.3.1 Simple regression for the aggregated primary categories, 1987 - 1996

The ratio of area of dwarf shrub vegetation to invasive species in pixel accounted for 3% of the variation in percentage change in area off dwarf shrub vegetation between 1987 and 1996 (Table 5.11). The inverse relationship was unexpected (Fig. 5.24). It had been hypothesised that as area of dwarf shrub vegetation increased, percentage change declined. Further, it is clear from Figure 5.24 that the relationship violates several regression assumptions. For example, neither the data nor the residuals are normally distributed. Again, multiple regression was not carried out as a result of the small coefficients of determination.

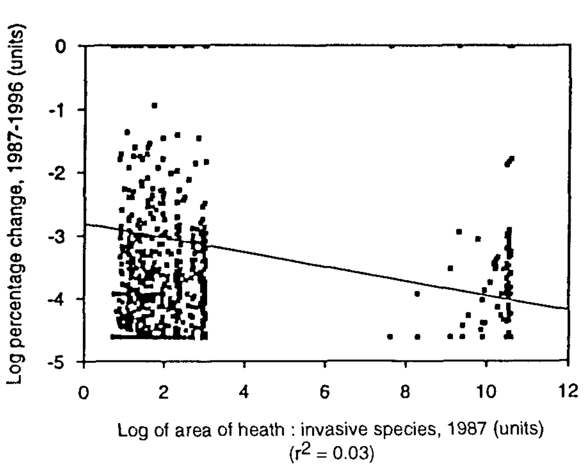


Fig. 5.24 Scatterplot of log area of dwarf shrub vegetation, 1987-1996 against log ratio of area of dwarf shrub vegetation to invasive species in a pixel, 1987.

Table 5.11. Simple regression for percentage change in area of dwarf shrub vegetation versus pixel-based aggregated primary categories, 1987.

Logged, pixel-based, explanatory variables	*df*	*p*	r^2	*Ho*/*H*1	Relationship
Area of heath : invasive species in a pixel	1, 1372	7.5e-10	0.03	*Ho*	Negative

5.7.4 Regression for the primary categories, 1987 - 1996

Simple regression was carried out to account for percentage change in area of dry heath, wet heath, humid heath and peatland in turn. However, no variable was significantly correlated with percentage change in area of dry heath, wet heath and humid heath in a pixel between 1987 and 1996.

5.7.4.1 Simple regression for area of peatland, 1987 - 1996

Percentage change was correlated with a single variable (Table 5.12). The area of peatland in a pixel accounted for 3% of the variation in percentage change. The relationship was as hypothesised (Fig. 5.25). As area increased, percentage change decreased.

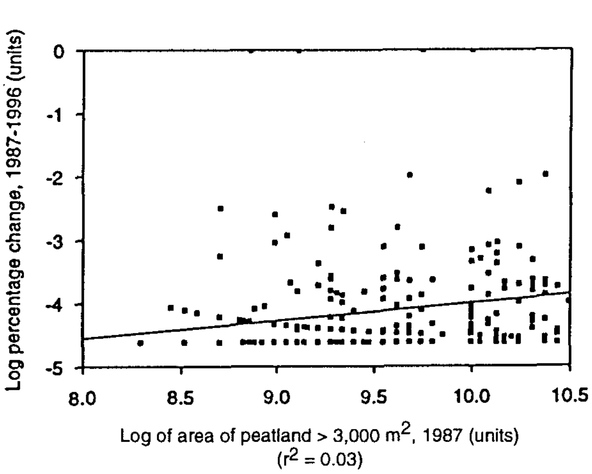


Fig. 5.25 Scatterplot of log percentage change in area of peatland, 1987-1996 against log area of peatland (> 3,000 m^2) in a pixel, 1987.

Table 5.12. Simple regression results for percentage change in area of heath versus pixel-based aggregated primary categories, 1987.

Logged, pixel-based, explanatory variables	*df*	*p*	r^2	*Ho*/*H*1	Relationship
Area of peatland in a pixel	1, 283	0.003	0.03	*H*1	Negative

5.8 Summary and discussion

It was hypothesised that spatial characteristics affect vegetation change at the sub-patch level (in this case the pixel level) as patches are likely to be internally fragmented and the processes which result in areal change in dwarf shrub vegetation may, therefore, occur at the sub-patch level.

Heathland management, land use change and succession were the three processes in action in the lowland heathland of Dorset. The effects of management were partly removed by isolating percentage increases in dwarf shrub vegetation and removing them. However, the effect of land use change could not be isolated, nor readily predicted. This research was primarily focused on the factors which influenced ecological change and whether spatial characteristics can predict change. It was hypothesised that several factors influenced percentage change (Chapter 2, 2.3.1). Such factors included, the initial area of dwarf shrub vegetation (or dwarf shrub vegetation type) in a pixel, the initial area of invasive species (or invasive species type) in a pixel, context (the distance a pixel lay from the edge) and density of invasive species surrounding a pixel. Factors such as patch geometry (size, shape and perimeter) could not influence change as a pixel is of fixed size and shape, in this case a cell of 200 m by 200 m

To test the new set of hypotheses (see Chapter 3, Table 3.7), several analyses were carried out. Histograms of the data were examined, feature space plots were developed to indicate what dwarf shrub vegetation (and the other aggregated primary categories) were changing to. Percentage change in the aggregated primary and a selection of primary categories was mapped. Finally, regression (both simple and multiple) was carried out with the specific aim of isolating what factors, if any, influence change in area of dwarf shrub vegetation over time.

The areal analysis of change (Chapter 4, 4.3.1) indicated that change was occurring. Land use change appeared the dominant process causing change in area of dwarf shrub vegetation between 1978 and 1987 with succession also playing a lesser rôle. The rôles reversed between 1987 and 1996. However, it was not clear what the dwarf shrub vegetation was changing to. Percentage change in area of invasive species was plotted against percentage change in area of dwarf shrub vegetation to examine what was replacing dwarf shrub vegetation. Percentage change in area of 'others' was also plotted against percentage change in area of dwarf shrub vegetation for the same reason. Both invasive species and land use change were replacing the declining areas of dwarf shrub vegetation. This trend occurred between 1978 and 1987. However, between 1987 and 1996 an increase in invasive species appeared to cause most of the decreases in area of dwarf shrub vegetation.

Regression was the method chosen to isolate the factors influencing the patterns of change identified previously. Percentage change in area of dwarf shrub vegetation between 1978 and 1987 was negatively correlated with area of dwarf shrub vegetation in a pixel in 1978. As the area of dwarf shrub vegetation in a pixel increased so did percentage change. Simple regression at the primary category level produced similar results. Percentage change in area of dwarf shrub vegetation between 1987 and 1996 was also negatively correlated with area of dwarf shrub vegetation ($r^2 = 0.47$). At the primary category level, percentage change was consistently negatively correlated with area. Therefore, simple regression analysis appeared overwhelmingly to indicate that on a pixel basis, the greater the areal extent of dwarf shrub vegetation (or dwarf shrub vegetation type), the greater the percentage change over time.

There was no ecological basis for the negative relationship between percentage change and area. Therefore, the data were analysed in an attempt to discover the cause of such a relationship. The smallest possible area of dwarf shrub vegetation in a pixel was 2,000 m^2 based on the use of a scale of between zero and three to account for presence or absence of a vegetation type during surveying. An investigation of the data indicated that log transforming the data affected small areas (which could only change by 0% or 100%) differently to larger areas, thus biasing the analysis and resulting in the negative relationship between percentage change and area. Therefore, pixels containing areas of dwarf shrub vegetation of 3,000 m^2 or less were removed and the regression analysis repeated. Simple regression analysis on the alternate data at the primary category level indicated that percentage change in area of dry heath in a pixel between 1978 and 1987 was positively correlated with area of dry heath in a pixel (Table 5.12). Although the relationship was now positive and therefore, as hypothesised, the coefficient of determination fell from 0.34 to 0.02.

Simple regression to examine percentage change between 1987 and 1996 at the aggregated primary category level and at the primary category level produced similar results. Because of the large number of data used in the analysis, a coefficient of determination of 0.02 was statistically significant. However, such small coefficients of determination are not useful as predictors of change. Further, as a 95% confidence interval was used, to reject the null hypothesis (H*o*) that a statistically significant relationship did not occur through chance, more than four relationships (at the aggregated primary category level and more than two at the primary category level) were required to be significant. This was often not the case. Therefore, it was not always possible to reject the null hypothesis. That is, the few statistically significant relationships which did occur, may have been the result of chance.

It is reasonable to conclude that despite the small coefficients of determination, percentage change in area of dwarf shrub vegetation is not well accounted for by any of the variables used in the analysis.

Table 5.12 Summary of relationships from simple regression. ♣ indicates that the hypothesis has been accepted, ♦ indicates that the relationship was contrary to that hypothesised.

Response variable: %change in area of heath			**Response variable: %change in heath type**	**Dry Heath**		**Wet Heath**		**Humid Heath**		**Peatland**	
Explanatory variables	**H_1 78-87**	**H_1 87-96**	**Explanatory variables**	**H_1 78-87**	**H_1 87-96**	**H_1 78-87**	**H_1 87-96**	**H_1 78-87**	**H_1 87-96**	**H_1 78-87**	**H_1 87-96**
1. Area of heath	♣		Area of dry heath	♣							
			Area of wet heath								
			Area of humid heath								
			Area of peatland							♣	♣
2. Area of invasive species			Area of scrub								
			Area of carr								
			Area of woodland								
3. Area of 'others'											
4. Area of heath:invasive species		♦	Area of heath:scrub								
			Area of heath:carr								
			Area of heath:woodland								
5. Area of heath : 'others'											
			Area of heath:dry heath								
			Area of heath:wet heath								
			Area of heath:humid heath								
			Area of heath:peatland								
6. Distance from edge			Distance from edge	♣							
7. Managed			Managed								

One hypothesis which did not prove significant and had been hypothesised to have a significant influence of percentage change was the density of invasive species surrounding a pixel. The per-patch analysis indicated there was a relationship between percentage change and area of invasive species. Therefore, the area of invasive species in a moving window around a pixel was examined. Despite altering the kernel size (it ranged between 200 m and 800 m) no significant correlations resulted. Further, it had been hypothesised that the further a pixel lay from the edge, the less susceptible it was to change (as edge effects lessen with increasing distance from the edge). However, no significant relationship resulted. The lack of a significant relationship between percentage change and density of invasive species surrounding a pixel and the distance a pixel lay from the edge of a patch were probably a result of both noise (in particular, the effect of land use change) and the scale of the analysis.

5.9 Conclusions

The pixel-based analysis was undertaken as an alternative to the patch-based analysis. The signal (initially identified during the per-patch analysis) which indicated that several variables influenced change was still present. However, the relationships which were weak at the patch level were now insignificant at the pixel level. Initially, the per-pixel analysis had seemed a promising approach, the large coefficients of determination indicating strong relationships between percentage change and area. The alternate relationships produced much smaller coefficients of determination. However, percentage change decreased with increasing area of dwarf shrub vegetation. In all, the pixel-based analysis did not result in a single significant predictive model. The small coefficients of determination are likely to be the result of the scale of the analysis.

CHAPTER 6

ANALYSING FOR THE EFFECTS OF MANAGEMENT

6.1 Introduction

Heathland management maintains the range of heathland habitats required to support its characteristic flora and fauna including areas of bare ground and heathland grasses, gorse and scrub, wet heathland, valley mire and open water. Dwarf shrub vegetation must be actively managed to ensure that the full range of growth stages are present and to encourage them to regenerate successfully (see Chapter 2, 2.2.3). In the absence of management, lowland heathlands tend to be invaded by *Pteridium aquilinum*, scrub species such as *Ulex europaeus, Betula spp., Pinus spp.* and *Rhododendron ponticum* and are eventually replaced by woodland (Michael, 1992). Since 1987 many differing management practices have been implemented on the heathlands of Dorset (little management was carried out between 1978 and 1987). Therefore, the aim of this chapter is to establish what effect management practices had on the dwarf shrub vegetation of Dorset. It is reasonable to expect that some management practices are more effective than others, and these practices should be identified in order to aid the conservation of the heathlands. Since the Dorset Heathland Surveys were carried out in 1978, 1987 and 1996, the management data were divided into two categories: management carried out between 1978 and 1987 and between 1987 and 1996. Thirteen different management practices were utilised:

1. Gorse coppicing
2. Bracken cutting
3. Foraged
4. Pine removal
5. Bracken spraying
6. Grazing
7. Scrub clearance
8. Sand patches created
9. Rhododendron clearance
10. Heather re-establishment
11. Controlled burning
12. Mowing
13. Wild fire

Although wildfire is not strictly a type of management, it was included because it results from anthropogenic activities and can substantially alter the ecology of a heathland environment.

The most extensive heathland management projects did not commence until after the second Dorset Heathland Survey (1987) results were published, making the heathland managers aware of quite how precarious the survival of the heathlands had become. In particular, the marked increase in scrub and trees between 1978 and 1987 (calculated in this research as a 9% increase) led to the implementation of large programmes of conservation management (Auld *et al.*, 1992; Woodrow *et al.*, 1996; Rose *et al.*, 1999).

Three processes were identified as being the likely cause of change in the heathlands of Dorset. Two of these have been investigated previously (land use change and succession), while the third process was heathland management. Although management did not result in natural ecological change, it was an important process, the effect of which has not previously been measured across all Dorset.

Management acts in two ways: it arrests the process of succession leading to increases in the areal extent of dwarf shrub vegetation and it lessens the percentage decreases in area of dwarf shrub vegetation over time (Webb, 1990). Therefore, a distinction was drawn between natural ecological change (succession) which can lead to a decline in area of dwarf shrub vegetation and human-induced change (management) which may result in an increase in area of dwarf shrub vegetation. Initially, if the area of dwarf shrub vegetation in a patch or pixel increased as a percentage of initial area between 1978 and 1987 or between 1987 and 1996 then such patches or pixels were isolated and included in an analysis of the affect of management on area of dwarf shrub vegetation. It was hypothesised that management would result in percentage increases in area of dwarf shrub vegetation.

A second analysis was carried out to examine the effect of management on percentage decreases in area of dwarf shrub vegetation. It was hypothesised that percentage decreases would lessen with increasing management. To facilitate both of these analyses, management data were obtained for the heathlands of Dorset in their entirety. The data were used to determine patches (and pixels) of dwarf shrub vegetation which have undergone human-induced change between 1978 and 1996. It should be recognised that the data were not sampled randomly. Indeed, the areas which underwent management were likely to have been specifically chosen by heathland managers, thus biasing the data. Initially, a patch-based approach to analysing change was taken, followed by a pixel-based approach. In each case, the aggregated primary categories, primary categories and secondary categories were examined in turn.

6.2 Summarising the data distributions

Histograms of patch-based percentage decreases were plotted previously (Chapter 4, Fig. 4.1a-i). Similarly, histograms of pixel-based percentage decreases have previously been

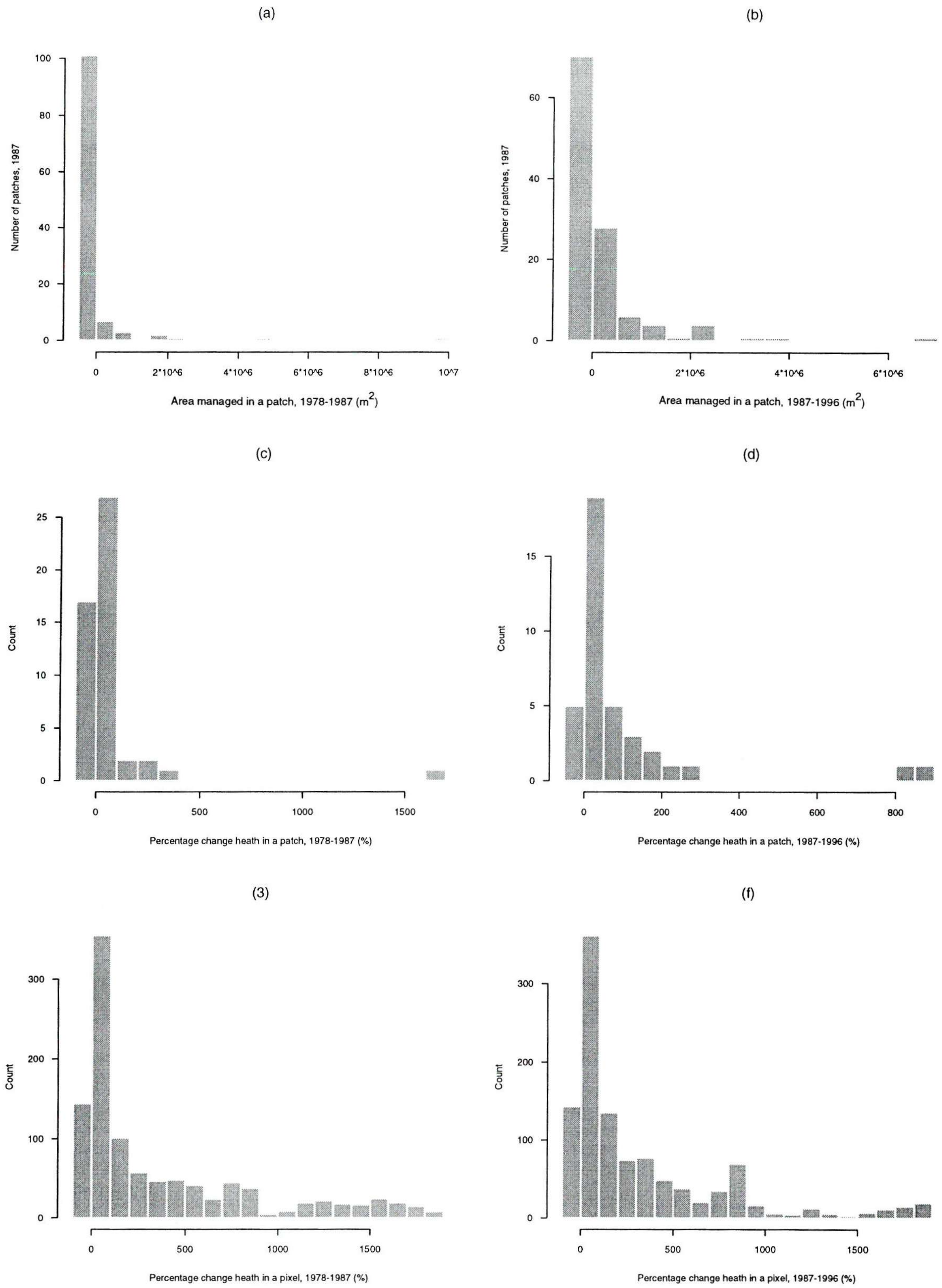


Fig. 6.1 Histograms of (a) area of a patch managed, 1978-1987 (m^2); (b) area of a patch managed, 1987-1996 (m^2); (c) percentage increases in area of dwarf shrub vegetation in a patch, 1978-1987 (%); (d) percentage increases in area of dwarf shrub vegetation in a patch, 1987-1996 (%); (e) percentage increases in area of dwarf shrub vegetation in a pixel, 1978-1987 (%); (f) percentage increases in area of dwarf shrub vegetation in a pixel, 1987-1996.

plotted (Chapter 5, Fig. 5.1a-i). Therefore, histograms of the patch- and pixel-based percentage increases were plotted.

The area of dwarf shrub vegetation in patch that was managed between 1978 and 1987 was plotted (Fig. 6.1a). The vast majority of patches were not managed in any way. The areas which were managed tended to be small, the mean area managed being just 0.1 km^2. However, between 1987 and 1996 the area managed increased (Fig. 6.1b). Again, the majority of patches were not managed but a considerable number were. The mean area of a patch managed between 1987 and 1996 was 0.3 km^2. The area managed increased between 1987 and 1996 largely because the area of dwarf shrub vegetation was in decline while the area of invasive species increased resulting in a rise in management activities.

Histograms of percentage increases were also plotted. Initially, percentage change between 1978 and 1987 was plotted (Fig. 6.1c). Where the area of dwarf shrub vegetation increased, it tended to be substantial. The area of dwarf shrub vegetation increased by about 100% in many patches (in which the area increased or remained unchanged), the mean percentage increase being 73.3%. However, many patches remained unchanged. Percentage change between 1987 and 1996 was similar (Fig. 6.1d). When the area of dwarf shrub vegetation increased, the increase tended to be large. Indeed, the area of dwarf shrub vegetation increased by 100% or more in many patches. The mean reflected this (94.9%). Fewer patches remained unchanged between 1987 and 1996 than between 1978 and 1987.

Histograms of the area of a pixel managed were not plotted because a pixel was either managed as a whole or not at all. However, histograms of percentage change in area of dwarf shrub vegetation in a pixel were plotted (Fig. 6.1e-f). The pixel-based histograms reflected those outlined above (Fig. 6.1c-d) and therefore will not be described in any detail. Between 1978 and 1987 and between 1987 and 1996 percentage increases tended to be substantial (in excess of 100%).

6.3 Feature space plots

Feature space plots of percentage decreases in area of dwarf shrub vegetation, invasive species and 'others' were plotted previously on a patch (Chapter 4, Fig. 4.2a-f) and pixel basis (Chapter 5, Fig. 5.2a-f). Therefore, feature space plots of patch-based increases were plotted. However, the pixel-based space plots are not illustrated because of their similarity with the patch-based feature space plots (Fig. 6.2a-f).

The patch-based plots indicated whether the percentage increases in area of dwarf shrub vegetation (in a patch) resulted from declining areas of invasive species (most likely the result of management) or fewer land use changes. Percentage change in area of invasive species was plotted against percentage change in area of dwarf shrub vegetation between 1978 and 1987 (Fig. 6.2a). The area of invasive species decreased in the majority of patches in which the areal extent of dwarf shrub vegetation increased. Percentage change in area of 'others' was plotted against percentage change in area of invasive species (Fig. 6.2b). Neither variable appeared to influence percentage change in the other. However, when percentage change in area of 'others' was plotted against percentage change in area of dwarf shrub vegetation, as the area of dwarf shrub vegetation increased, the area of 'others' decreased (Fig. 6.2c). The percentage increases in area of dwarf shrub vegetation tended to be quite large. Between 1978 and 1987 increased areal extent of dwarf shrub vegetation appeared to result from a reduction in the areal extent of both invasive species and 'others'.

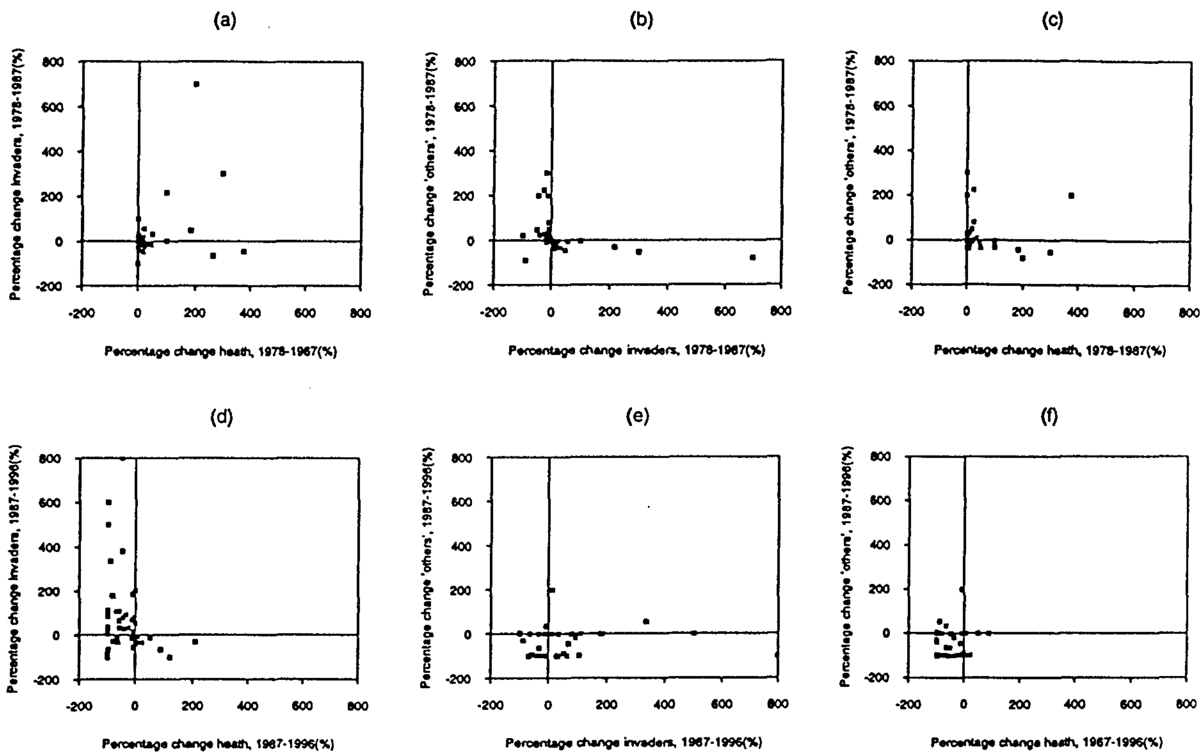


Fig. 6.2 Feature space plots of (a and d) percentage change in area of invasive species against percentage change in area of dwarf shrub vegetation; (b and e) percentage change in area of 'others' against percentage change in area of invasive species; (c and f) percentage change in area of 'others' against percentage change in area of dwarf shrub vegetation.

The analysis was repeated to examine the likely cause of percentage increases in area of dwarf shrub vegetation between 1987 and 1996. The results reflected those outlined above (Figs 6.2a-c). Percentage decreases in area of invasive species appeared to account for percentage increases in the area of dwarf shrub vegetation (Fig. 6.2d). Indeed, the percentage increases were, in many patches, large. Percentage change in area of 'others' did not appear to cause a decline in area of invasive species (Fig. 6.2e). However, as the area of 'others' decreased, the area of dwarf shrub vegetation appeared to increase in several patches (Fig. 6.2f).

The area of dwarf shrub vegetation did not remain unchanged or increase in many patches (fifty between 1978 and 1987 and thirty one between 1987 and 1996). The main difference between causes of change between 1978 and 1987 and between 1987 and 1996 was the influence of 'others' and invasive species. Between 1978 and 1987, changing land use appeared to influence percentage increases in area of dwarf shrub vegetation more than changing area of invasive species. The opposite appeared to be true between 1987 and 1996. Although it had been hypothesised that management would account for any percentage increases in area of dwarf shrub vegetation over time, the process of change appeared to be more complicated with changing land use playing a rôle.

6.4 The area over which dwarf shrub vegetation was managed

The area of management in Dorset was mapped. Managed pixels, rather than patches, were mapped to indicate just how few areas of dwarf shrub vegetation were actively managed. Gorse coppicing, bracken spraying and cutting, pine removal and scrub clearance were the most common forms of management practice. However, foraging, rhododendron clearance, burning, grazing, heather re-establishment and mowing were also carried out. Initially, the area of dwarf shrub vegetation actively managed between 1978 and 1987 was mapped (Fig. 6.3). Few areas were managed (299 pixels out of a possible 3,110) and of the areas that were, many different management practices were used. Between 1987 and 1996, there was a substantial rise in the areal extent of management practices (399 pixels) (Fig. 6.4). The majority of patches or clusters of pixels were actively managed in some way. Scrub, pine and bracken control remained the most common management practices.

6.5 Bivariate analysis of change

To examine the trends and patterns of change in the dwarf shrub vegetation of Dorset quantitatively, simple regression was used. Simple regression was carried out with the aim of isolating factors which influenced percentage increases and decreases in area of dwarf shrub vegetation. First, a patch-based analysis to examine the relationship between percentage increases and the explanatory variables was carried out. The analysis was repeated at a pixel

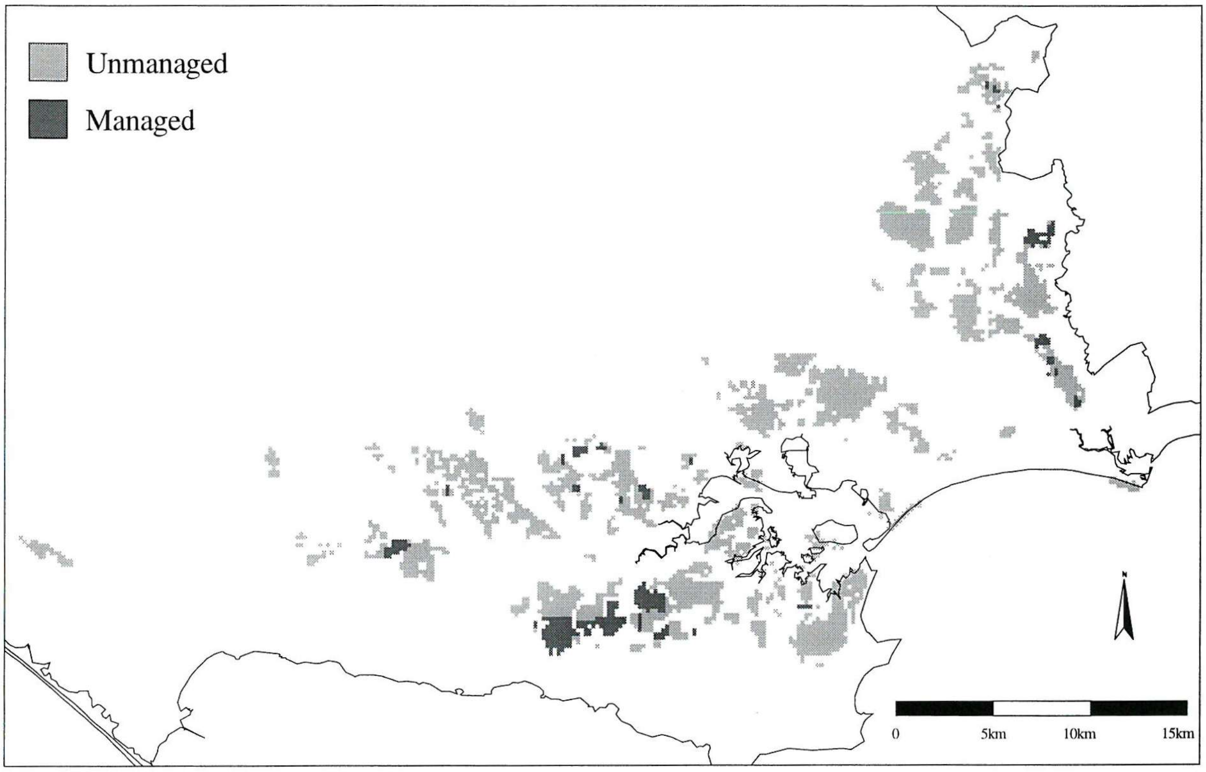


Fig. 6.3 Area of dwarf shrub vegetation managed in a patch, 1978 –1987

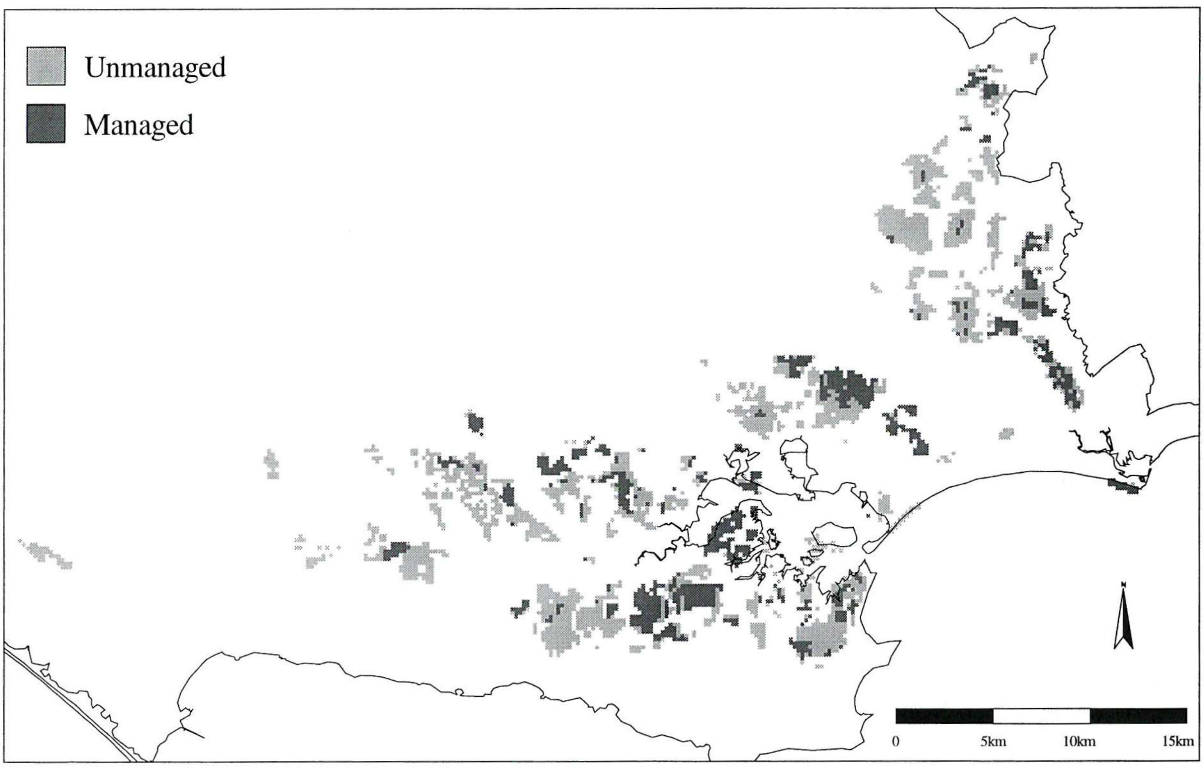


Fig. 6.4 Area of dwarf shrub vegetation managed in a patch, 1987 –1996

level. Second, a patch-based analysis to examine the relationship between percentage decreases and the explanatory variables was carried out. Again, the analysis was repeated at a pixel level.

The patch-based analysis explanatory variables included the proportion of a patch managed, and the proportion of a patch which underwent different types of management (see Table 6.1). It was hypothesised that the explanatory variables would account for percentage increases in area of dwarf shrub vegetation (or dwarf shrub vegetation type). That is, the greater the area managed, the greater the increase in area of dwarf shrub vegetation. There was one exception, wild fire can damage the dwarf shrub vegetation postponing the development of dwarf shrub vegetation (Bullock & Webb, 1995).

The pixel-based explanatory variables (and, therefore, the hypotheses) were identical to those used for the patch-based analysis (Table 6.1). However, the area of a patch managed was not included.

Table 6.1 Hypotheses tested using explanatory variables.

Management variables to test their influence on percentage change	**Hypotheses tested**
1. Proportion managed	The greater the proportion managed, the greater the percentage increase in area of dwarf shrub vegetation over time
2. Proportion where gorse coppiced	Ditto
3. Proportion foraged	Ditto
4. Proportion where bracken sprayed	Ditto
5. Proportion where scrub cleared	Ditto
6. Proportion where rhododendron cleared	Ditto
7. Proportion which underwent controlled burning	Ditto
8. Proportion where wild fire took place	The greater the area, the smaller the percentage increase in area of dwarf shrub vegetation over time
9. Proportion where bracken cutting took place	The greater the proportion managed, the greater the percentage increase in area of dwarf shrub vegetation over time
10. Proportion where pine removed	Ditto
11. Proportion grazed	Ditto
12. Proportion where heather re-establishment carried out	Ditto
13. Proportion mowed	Ditto

Percentage decreases in area of dwarf shrub vegetation (and dwarf shrub vegetation type) were also analysed, initially at a patch level, but followed by a pixel-based analysis. It was hypothesised that management would arrest the process of succession, resulting in a lesser percentage decrease in area of dwarf shrub vegetation (or dwarf shrub vegetation type) over time. The explanatory variables reflected those used in the analysis of percentage increases (Table 6.1).

6.6 Bivariate analysis of percentage increases in area of dwarf shrub vegetation

As management arrests succession, it was likely that percentage change (increases) in area of dwarf shrub vegetation in a patch or a pixel would increase with management. Therefore, the relationship between percentage change (increases) and management (or management type) on a patch and a pixel basis was examined. The analysis was carried out at two levels. First, the effect of management was examined and second, the effect of management type was examined.

6.6.1 Patch-based analysis

Following the procedure outlined in Chapter 4 (section 4.7.1), when the area of dwarf shrub vegetation (or dwarf shrub vegetation type) in a patch was zero, the patch was removed from the analysis. If such patches had not been removed, percentage change in area of dwarf shrub vegetation would have been zero in several patches because the patches did not contain any dwarf shrub vegetation (or dwarf shrub vegetation type) rather than because the area of dwarf shrub vegetation (or dwarf shrub vegetation type) remained unchanged, thereby, biasing the data. For example, when percentage change in area of wet heath was examined, many patches did not contain any wet heath and were, therefore, recorded as undergoing zero percentage change over time. If a patch which did not contain wet heath was managed, then there is a chance that management and the zero change would be correlated. If there was a correlation then it would be false, resulting from the modelling procedure rather than any real relationship. Therefore, at the aggregated primary category level and at the primary category level, patches which did not contain dwarf shrub vegetation were removed.

Initially, change in area of dwarf shrub vegetation between 1978 and 1987 was examined on an aggregated primary category level. No significant relationships emerged. The analysis was repeated at the primary category level but again, no significant relationships resulted. None of the explanatory variables accounted for a significant amount of the variation in percentage change.

Change in area of dwarf shrub vegetation between 1987 and 1996 was examined. There were no significant regression results when percentage change in area of dwarf shrub vegetation was regressed against each explanatory variable. The regression analysis was repeated at the primary category level. However, no variable was significantly correlated with percentage change in area of dry heath or humid heath.

6.6.1.1 Simple regression for percentage change in area of wet heath, 1987-1996

The relationship between percentage change in area of wet heath between 1987 and 1996 and *management* was examined first. The proportion of a patch managed accounted for 10% of the variation in percentage change. However, the inverse relationship was not as hypothesised (Fig. 6.5a).

Table 6.2. Simple regression for percentage change in area of wet heath versus patch-based aggregated primary categories, 1987. Only significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2	Ho/H_1	**Relationship**
The proportion of a patch managed	1, 32	0.071	0.10	*Ho*	Negative

When the relationship between percentage change and *management type* was analysed, percentage change was significantly correlated with the proportion of a patch managed using bracken spraying (r^2 = 0.14) (Table 6.3). The positive relationship was as hypothesised, the greater the proportion managed the greater the increase in area of wet heath (Fig. 6.5b). Bracken spraying is frequently used by heathland managers. Therefore, the relationship between percentage increases and this management type makes sense.

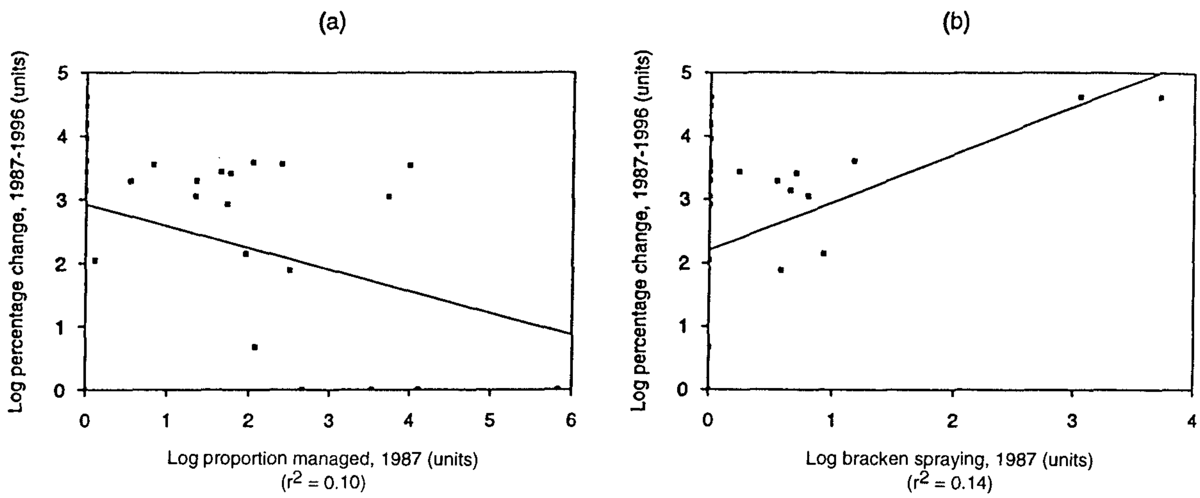


Fig. 6.5 Scatterplots of (a) log percentage change (increases) in area of wet heath, 1987-1996 against log proportion of a patch managed, 1987; (b) log percentage change (increases) in area of wet heath, 1987-1996 against log proportion of a patch managed with bracken spraying, 1987.

Table 6.3. Simple regression for percentage change in area of wet heath versus patch-based aggregated primary categories, 1987. Only significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2	Ho/H_1	Relationship
Bracken spraying	1, 32	0.032	0.14	H_1	Positive

6.6.1.2 Multiple regression for percentage change in area of wet heath, 1987-1996

Multiple regression was carried out to examine the relationship between percentage change and management type (Table 6.4). The proportion of a patch where bracken was sprayed accounted for most variation in percentage change and the proportion of a patch cleared of pine accounted for a significant portion of the residuals. Therefore, when the influence of bracken spraying was removed, percentage change was significantly related with the proportion of a patch cleared of pine. Like bracken spraying, pine clearance (particularly, the removal of pine seedlings) is one of the most common forms of heathland management carried out in Dorset. Therefore, the relationship between percentage change and pine clearance was not unexpected.

Table 6.4. Multiple regression for percentage change in area of wet heath versus patch-based aggregated primary categories, 1987. Only significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2
Bracken spraying	1, 32	0.032	0.14
+ Pine clearance	2, 31	0.031	0.20

6.6.1.3 Simple regression for percentage change in area of peatland, 1987-1996

Percentage change was not significantly correlated with the proportion of a patch managed. Despite this, percentage change in area of peatland between 1987 and 1996 was significantly correlated with the proportion of a patch cleared of rhododendron (Table 6.5) ($r^2 = 0.14$). The positive relationship was as hypothesised (Fig. 6.6). The greater the proportion of the patch managed in this way, the greater the percentage increase in area of peatland.

Table 6.5. Simple regression for percentage change in area of peatland versus patch-based aggregated primary categories, 1987. Only significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2	Ho/H_1	Relationship
Rhododendron clearance	1, 25	0.056	0.14	H_1	Positive

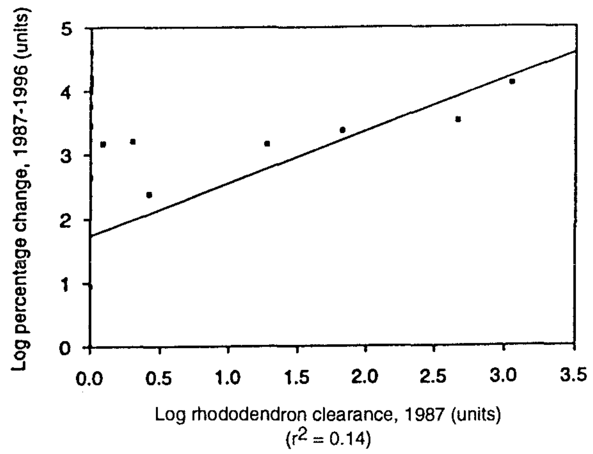


Fig. 6.6 Scatterplot of log percentage change (increases) in area of peatland, 1987-1996 against log area of a patch managed by rhododendron clearance, 1987.

6.6.1.4 Multiple regression for percentage change in area of peatland, 1987-1996

Percentage change was most highly correlated with the proportion of a patch managed through rhododendron clearance (Table 6.6). When the influence of rhododendron clearance was held constant, percentage change was significantly correlated with the proportion of a patch managed by pine clearance. The proportion of a patch managed though scrub clearance accounted for a significant part of the remainder. Therefore, these three management types influenced percentage change (increases) in area of peatland in a patch. It is reasonable that percentage increases in area of peatland would be influenced by rhododendron, pine and scrub clearance as these (in conjunction with bracken spraying) are the most widely used types of management.

Table 6.6. Multiple regression for percentage change in area of peatland versus patch-based aggregated primary categories, 1987. Only significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2
Rhododendron clearance	1, 25	0.056	0.14
+ Pine clearance	2, 24	0.048	0.22
+ Scrub clearance	3, 23	0.089	0.24

6.6.2 Pixel-based analysis

As for the patch-based analysis, any pixels which did not contain dwarf shrub vegetation (or dwarf shrub vegetation type) in 1978 and 1987 were isolated, removed and excluded from the regression analysis. Further, pixels containing the smallest possible area of dwarf shrub vegetation (2,000 m^2) were also removed from the analysis (see Chapter 5, 5.8).

No explanatory variables were significantly correlated with percentage change (increases) in area of dwarf shrub vegetation between 1978 and 1987 and between 1987 and 1996 in a pixel. The analysis was repeated at a primary category level but again no variable was significantly correlated with percentage change in area of dry heath, wet heath, humid heath and peatland between 1978 and 1987, and 1987 and 1996.

6.7 Bivariate analysis of percentage decreases in area of dwarf shrub vegetation

As management arrests succession, it was likely that percentage decreases in area of dwarf shrub vegetation in a patch or a pixel would lessen with management. Therefore, the relationship between percentage decreases and management (and management type) on a patch and a pixel basis was examined.

6.7.1 Patch-based analysis

No explanatory variables were significantly correlated with percentage change in area of dwarf shrub vegetation between 1978 and 1987 and between 1987 and 1996. The analysis was repeated at a primary category level but again no variable was significantly correlated with percentage change in area of dry heath, wet heath or humid heath between 1978 and 1987, and 1987 and 1996. However, percentage change in area of peatland between 1987 and 1996 was significantly correlated with two variables.

6.7.1.1 Simple regression for percentage change in area of peatland, 1987-1996

The proportion of a patch managed accounted for 15% of the variation in percentage change in area of peatland between 1987 and 1996 in a patch (Table 6.7). The positive relationship was as hypothesised (Fig. 6.7a). The greater the proportion of the patch managed, the less the percentage decrease in area of peatland.

Table 6.7. Simple regression for percentage change in area of peatland versus patch-based aggregated primary categories, 1987. Only significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2	*Ho*/H_1	**Relationship**
Proportion of a patch managed	1, 37	0.014	0.15	H_1	Positive

Percentage change in area of peatland between 1987 and 1996 was also positively correlated with the proportion of a patch cleared of pine (Table 6.8). Again the relationship was as hypothesised, pine removal apparently arrested the process of succession (Fig. 6.7b).

Table 6.8. Simple regression for percentage change in area of peatland versus patch-based aggregated primary categories, 1987. Only significant relationships are shown.

Logged, patch-based explanatory variables	df	p	r^2	Ho/H_1	Relationship
Pine clearance	1, 37	0.009	0.17	H_1	Positive

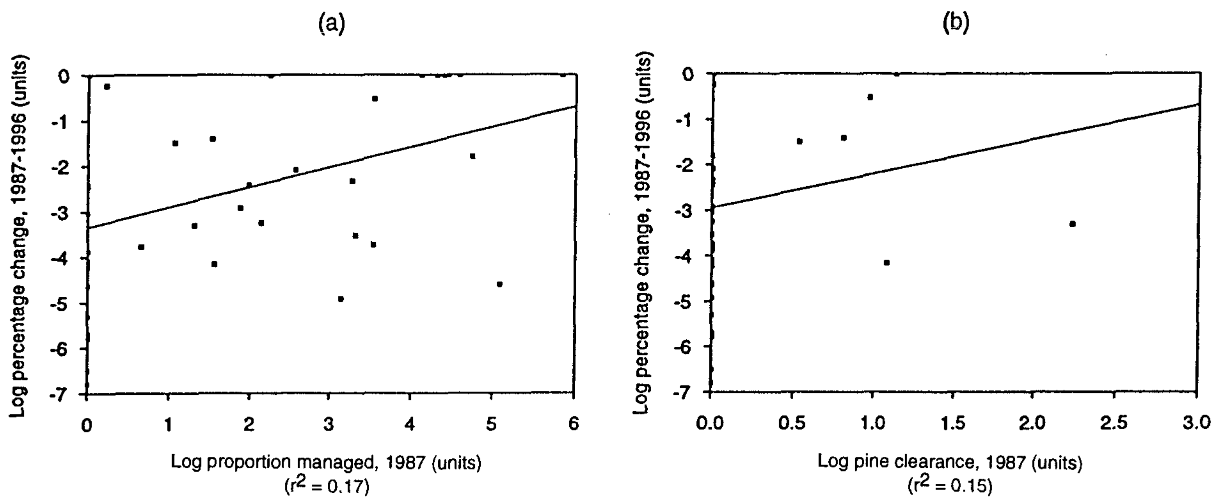


Fig. 6.7 Scatterplots of (a) log percentage change (decreases) in area of peatland, 1987-1996 against log proportion of a patch managed, 1987; (b) log percentage change in area of peatland, 1987-1996 against log area of patch managed by pine clearance, 1987.

6.7.1.2 Multiple regression for percentage change in area of peatland, 1987-1996

Multiple regression revealed percentage change was significantly correlated with three variables (Table 6.9). When the influence of pine clearance was held constant, the proportion of a patch managed through controlled burning accounted for a significant part of the residuals and the proportion of a patch grazed, a significant amount of the remainder. Therefore, it appeared that each of the three management practices could arrest the process of succession leading to lesser percentage decreases in area of peatland in a patch between 1987 and 1996. Again, the relationship between percentage change and pine clearance is reasonable as it is a commonly used method of management. Managed burning and grazing are also often used to manage the heathlands of Dorset, but their use is not quite so widespread. Despite this, both methods appear to be effective.

Table 6.9. Multiple regression for percentage change in area of peatland versus patch-based aggregated primary categories, 1987. Only significant relationships are shown.

Logged, patch-based explanatory variables	*df*	*p*	r^2
Pine clearance	1, 37	0.009	0.17
+ Managed burning	2, 36	0.020	0.19
+ Grazing	3, 35	0.039	0.21

6.7.2 Pixel-based analysis

Neither management nor management type were significantly correlated with percentage change in area of dwarf shrub vegetation between 1978 and 1987 and between 1987 and 1996. The analysis was repeated at the primary category level but again no variable was significantly correlated with percentage change in area of dry heath, wet heath, humid heath or peatland between 1978 and 1987, and 1987 and 1996.

6.8 Summary and discussion

The management of the dwarf shrub vegetation in Dorset aimed to arrest the process of succession and prevent further losses. When traditional management practices died out in the latter half of this century, the dwarf shrub vegetation was left to its own devices. As all heathlands are semi-natural, when management stopped succession increased. Between 1978 and 1987 little management was carried out. After the 1987 Dorset Heathland Survey, heathland managers became aware of the pressing need for management as the area of invasive species was increasing at a rate of 1% per annum. Despite an increase in the area of dwarf shrub vegetation managed between 1987 and 1996, the rate of increase in area of invasive species accelerated to 2% per annum. Therefore, this analysis aimed to identify if management prevented further losses of dwarf shrub vegetation and whether management facilitated increases in the areal extent of dwarf shrub vegetation over time. Further, the relationship between percentage change and each kind of management practice was examined.

Initially, percentage increases in area of dwarf shrub vegetation in a patch were examined (Table 6.10). Percentage change in area of wet heath between 1987 and 1996 was inversely correlated with the proportion of a patch managed. The inverse relationship was not as hypothesised: as the proportion of a patch managed increased, the percentage increase lessened. The relationship may have resulted because management merely arrests succession and, in general, does not directly result in increased areal extent. However, no clear reason for the relationship was apparent. Percentage change and management type were also analysed. One significant relationship resulted. Percentage change was significantly correlated with the proportion of a patch managed using bracken spraying. The positive relationship was as hypothesised. Multiple regression indicated that when the influence of bracken spraying was held constant, the area cleared of pine influenced percentage increases in area of wet heath. Both bracken spraying and pine clearance appeared to account for some percentage increases in area of wet heath in a patch between 1987 and 1996.

Percentage change in area of peatland between 1987 and 1996 was not significantly correlated with the proportion of a patch managed (Table 6.10). The lack of a significant relationship between percentage increases and the proportion of a patch managed may have resulted because management is never applied evenly over an area. Rather, it is concentrated in the areas which are most in need of management. Percentage change was significantly and positively correlated with management type, in this case the proportion of a patch which underwent rhododendron clearance. It appeared that the area of peatland may increase as a percentage of initial area if managed effectively (in this case through rhododendron clearance). Multiple regression indicated that percentage change was significantly related with three variables. Rhododendron clearance accounted for most variation in percentage change, pine clearance accounted for a significant portion of the residuals and scrub clearance a significant amount of the remainder. In all, rhododendron clearance, pine clearance and scrub clearance appeared to influence percentage increases in area of peatland in a patch.

Table 6.10 Summary of relationships from simple regression. ♣ indicates that the hypothesis has been accepted, ♦ indicates that the relationship was contrary to that hypothesised.

Response variable: %increases in area of heath			**Response variable: %increases in area of:**							
			Dry Heath		**Wet Heath**		**Humid Heath**		**Peatland**	
Explanatory variables	H_1 **78-87**	H_1 **87-96**	H_1 **78-87**	H_1 **87-96**	H_1 **78-87**	H_1 **87-96**	H_1 **78-87**	H_1 **87-96**	H_1 **78-87**	H_1 **87-96**
1. Proportion of a patch managed						♦				
2. Gorse coppicing										
3. Foraged										
4. Bracken spraying						♣				
5. Scrub clearance										
6. Rhododendron clearance										♣
7. Pine removal										
8. Grazing										
9. Controlled burning										
10. Wild fire										
11. Mowing										
12. Heather re-establishment										
13. Bracken cutting										

The relationship between percentage change (increases) and management on a pixel basis was also analysed. However, no significant relationships resulted either between percentage change and the area of a pixel managed, or between percentage change and management type. In all, it appeared that for some dwarf shrub vegetation types, certain management practices (and in the case of wet heath, the proportion of a patch managed) may result in a percentage increase in the area of dwarf shrub vegetation in a patch over time. However, at a pixel-level, percentage change and management appeared unrelated.

A second analysis was carried out to examine the relationship between percentage decreases in area of dwarf shrub vegetation and the proportion of a patch managed and the type of management (Table 6.11). Initially, percentage decreases in area of peatland between 1987 and 1996 was significantly and positively correlated with the proportion of a patch managed. The area of dwarf shrub vegetation declined less as a percentage over time as the proportion of a patch managed increased. Management appeared to arrest the process of succession in peatland. The relationship between percentage change and management type was also examined. Percentage change was significantly correlated with the proportion of a patch cleared of pine. As management increased, the percentage decrease lessened. Therefore, both management and management type (in the form of pine clearance) appeared to arrest the process of succession in peatland.

Table 6.11 Summary of relationships from simple regression. ♣ indicates that the hypothesis has been accepted, ♦ indicates that the relationship was contrary to that hypothesised.

Response variable: %decreases in area of heath			**Response variable: %decreases in area of:**							
			Dry Heath		**Wet Heath**		**Humid Heath**		**Peatland**	
Explanatory variables	H_1 78-87	H_1 87-96	H_1 78-87	H_1 87-96	H_1 78-87	H_1 87-96	H_1 78-87	H_1 87-96	H_1 78-87	H_1 87-96
1. Proportion of a patch managed										♣
2. Gorse coppicing										
3. Foraged										
4. Bracken spraying										
5. Scrub clearance										
6. Rhododendron clearance										
7. Pine removal										♣
8. Grazing										
9. Controlled burning										
10. Wild fire										
11. Mowing										
12. Heather re-establishment										
13. Bracken cutting										

Multiple regression analysis was carried out to examine the relationship between percentage decreases in area of peatland and management type. When the influence of pine clearance was removed, the proportion of a patch managed by controlled burning was significantly correlated with percentage change, as was the proportion of a patch grazed. Therefore, in peatland areas the process of succession seemed to be arrested by pine clearance, controlled burning and grazing. The relationship between percentage change and burning and grazing is particularly interesting as these are both traditional methods of heathland management.

Percentage change in area of peatland was consistently correlated with management. The most obvious reason for this is that peatlands are less likely to be subjected to land use change. Therefore, the effect of noise caused by 'others' is limited. It seemed that wetter dwarf shurb vegetation types (wet heath and peatland) were more responsive to management than drier dwarf shrub vegetation types (dry heath and humid heath) because it was these dependent variables for which significant coefficients of determination were found. It is not clear why this was the case, but suggests that it would be useful to study how different types of dwarf shrub vegetation respond to management.

The per-patch analysis to account for percentage change (decreases) in a patch produced few significant relationships. However, the per-pixel analysis was even less fruitful. Percentage change (decreases) in area of dwarf shrub vegetation (or dwarf shrub vegetation type) in a pixel was not significantly correlated with a single variable. This was unexpected. It had been hypothesised that percentage change would be positively related with management in a pixel. If a pixel was managed then succession should be arrested leading to a decline in percentage decreases in area of dwarf shrub vegetation or facilitating a percentage increase in area of dwarf shrub vegetation over time. Neither management as a whole nor management type appeared to influence percentage change in a pixel in any way. The reason for this was not apparent. Perhaps, the effect of management would only be noticeable when pixels in which the area of dwarf shrub vegetation increased, or where percentage decreases were lessened by management, were amalgamated. By amalgamating pixels to form patches, the effect of management would be revealed, leading to a positive relationship between percentage change and management. Further, if management was inaccurately assigned to a pixel (as may be the case with poor maps held by some management agencies), then the management data would be inaccurate geometrically. This may in part account for the lack of significant relationships between percentage change and management. At a patch level such inaccuracies would be removed by amalgamating the pixels. Whatever the cause, the anticipated pixel-based effect was not realized. The pixel-based analysis may have produced small coefficients of determination because so few pixels were managed, but it is more likely that data quality played a part.

6.9 Conclusions

In conclusion, on a patch level management appeared only to influence change at the primary category level. This is because the differing management practices are rarely applied equally across a patch or pixel and they are applied to different dwarf shrub vegetation types. Therefore, when analysing for the effect of management, it should be at a primary category level using management type rather than management as a whole. Management practices appeared to have the required effect, causing fewer decreases in area of peatland and some increases in area of both wet heath and peatland as a percentage of initial area. At the pixel level management appeared to have little affect. Also, it is important to remember that few areas of dwarf shrub vegetation were actively managed between 1978 and 1987, which may account for the absence of significant relationships on a patch and a pixel basis. The concerted effort to arrest the spread of succession between 1987 and 1996 appeared to fail as the area of invasive species increased by 1,454 km^2. As management appears to have had some effect (on wet heath and peatland) then the effort was not wasted. It remains to be seen if the process of succession continues to accelerate between 1996 and the next Dorset Heathland Survey in 2005.

CHAPTER 7

DISCUSSION

"All models are wrong, but some are useful"

George E.P. Box

7.1 Introduction

This chapter expands upon the patch- and pixel-based analyses carried out in Chapters 4, 5 and 6. Initially, the processes of change are summarised. Then the implications of the results of these analyses for the survival of the remaining areas of dwarf shrub vegetation of Dorset are discussed in detail. As well as discussing the significant results, an in-depth investigation of the likely causes of the lack of significant results in certain cases is also given. The effect of management activities is examined in relation to percentage change (increases and decreases) in area of dwarf shrub vegetation (and dwarf shrub vegetation type). Further, the results of these analyses are compared to other work on areal change in dwarf shrub vegetation in Dorset. Also, the broader implications for the analysis and mapping of landscape change will be discussed. The conclusions are drawn and discussed in terms of their relevance to the future management of the dwarf shrub vegetation of Dorset.

7.2 Processes of change

Four main processes causing change were consistently identified by each of the analyses. These were changing land use, heathland management, succession and within heathland switching between dwarf shrub vegetation types. The effect of land use change was discussed in detail in Chapter 4 (section 4.8). Land use change is not a natural ecological process. Further, there is little predictable pattern to land use change and, therefore, it should be unaffected by patch and pixel spatial characteristics. Land use change could neither be predicted nor modelled as it is not a function of initial area. Therefore, attempts were made to isolate and remove the effect of land use change with little success. Changing land use resulted in considerable change in the area of dwarf shrub vegetation between 1978 and 1987. However, its effect lessened between 1987 and 1996. Today, direct losses have virtually stopped. Conversion to farmland ceased when subsidies were withdrawn and urban industrial development is now controlled through planning and environmental legislation (Rose *et al.*, in press). Further losses due to land use change are unlikely.

The process of succession formed the rationale for the analysis of change outlined in Chapters 4, 5 and 6. Succession is a natural ecological process. It is probably a spatial process and, therefore, it was hypothesised that it would be affected by the spatial characteristics (and spatial composition) of a patch or pixel. It has long been recognised but little studied that the rate and pattern of succession may also reflect spatial factors (Glen-Lewin, 1992). However, this analysis aimed to build a model of change based on factors which affected both the rate and pattern of the spatial process of succession.

Management was discussed in detail in Chapter 6. Management is unlikely to be influenced by the spatial characteristics of a patch or pixel. It was hypothesised that management would arrest the process of succession and could even increase the area of dwarf shrub vegetation. However, as a result, management may also obscure the relationship between patch and pixel spatial characteristics and the process of succession.

The final process of change identified by all the analyses of change was the process of transitions between dwarf shrub vegetation types. In particular, the variation in wet heath and peatlands. Between 1978 and 1987 Rose *et al.* (in press) identified little change between the two dwarf shrub vegetation types. However, between 1987 and 1996 the area of wet heath declined by 45% and the area peatland by 25%. This analysis identified similar changes.

7.3 Patch-based approach

The patch-based model seemed a logical choice to analyse change in the dwarf shrub vegetation of Dorset (see Chapter 4, 4.2). The dwarf shrub vegetation of Dorset form a system of patches in a matrix of forest, agricultural and urban land. However, defining patches within any landscape is problematic. Often, it is very difficult to establish the biological criteria by which heathland fragments can be defined, since the criteria vary with the species under consideration (Webb, 1992). However, this research aimed to determine correlates of change in area of dwarf shrub vegetation in Dorset. Once dwarf shrub vegetation was defined for the purposes of this analysis, the process of defining a patch became more simple. Heathland was defined as any combination of dry heath, wet heath, humid heath and peatland. The analysis was based upon the Dorset Heathland Surveys of 1978, 1987 and 1996. The initial Dorset Heathland Survey was based around the premise that any pixel containing dwarf shrub vegetation should be surveyed. Therefore, it seemed reasonable to form patches by amalgamating a pixel containing any area of dwarf shrub vegetation with any pixel adjacent to or on a diagonal with a similar pixel, although other rules could have been used. For example, Webb and Haskins (1980) created patches based purely on physical isolation. Every area of heath which was not in contact with any other was considered separately. Chapman *et al.* (1989) amalgamated pixels with adjoining sides but pixels on the diagonals were only included when they were made up of at least 75% heathland or its associated vegetation types. Webb (1990) used a similar rule to Chapman *et al.* (1989). Finally, Rose *et al.* (in press) grouped pixels with some dwarf shrub heath or acid grassland based on the rules set out by Chapman *et al.* (1989). The method used for creating patches for the purposes of this research resulted in 116 patches, and these were used as a template for the 1987 and 1996 data.

7.3.1 Summation of the patch-based analysis

The patch-based approach aimed to test how percentage change in area of dwarf shrub vegetation (or dwarf shrub vegetation type) varied in relation to a series of explanatory variables. The explanatory variables were chosen because it was likely that they influenced the process of succession in a fragmented dwarf shrub vegetation environment (see Chapter 3, 3.5.2). The patch-based analysis of change produced three main results. First, percentage change was consistently correlated with the density of dwarf shrub vegetation (or dwarf shrub vegetation type) in a patch (or in the edge of a patch). Second, percentage change was consistently correlated with the area of invasive species (or invasive species type) in a patch (or in the edge of a patch). Third, percentage change was consistently correlated with the ratio of area of dwarf shrub vegetation type to the area of invasive species type in a patch (or in the edge of a patch).

The relationship between percentage change in area of dwarf shrub vegetation and density of dwarf shrub vegetation in a patch was interesting. Density relates to the degree of fragmentation of the area of dwarf shrub vegetation in a patch. Greater density implies less internal fragmentation of the dwarf shrub vegetation in a patch, and less fragmentation makes a patch less susceptible to change. Moore (1962) and Webb and Vermaat (1990), also found this to be the case. Succession depends upon proximity to a seed source of late successional species (Mitchell *et al.*, 1997). When the coverage of dwarf shrub vegetation within a patch is dense, it is less fragmented and the availability of a seed source within a patch less likely. Therefore, the process of succession in a dense patch of dwarf shrub vegetation is limited. Further, percentage change was also influenced by the density of dwarf shrub vegetation in the edge of a patch. It had been hypothesised that, as Webb (1992) stated, changes on a given patch are as much a result of successional processes within a patch as changes generated by the surroundings of a patch; hence, for a given patch its future will depend both on its present composition and where it is located in the landscape. Indeed, as hypothesised, the density of dwarf shrub vegetation in the edge of a patch (a surrogate variable for context) appeared as important as the density of dwarf shrub vegetation within a patch.

Edge pixels are precisely that. Every 200 m by 200 m square containing *any* area of dwarf shrub vegetation was surveyed. Therefore, many edge pixels contained little heath as they fell at the very edge of a fragment, and such pixels were invaluable as they provided an accurate assessment of a patches immediate surroundings. As suggested by Forman and Godron (1986) and Lavers and Haines-Young, (1993), the greater the density of dwarf shrub vegetation in the edge, the less fragmented the edge of a patch and, therefore, the less like an edge it behaves. That is, edges are more easily invaded because they juxtapose dwarf shrub vegetation and non-dwarf shrub vegetation species increasing the availability of a seed source for succession, and making the edge liable to succession. The relationship between percentage change and density of dwarf shrub vegetation in the edge was complex. It implied that edges where the area of dwarf shrub vegetation was less fragmented were less susceptible to change. Moore (1962) suggested that when a habitat is reduced in size, edge effects become important, and this appeared to be so. However, if an edge is not fragmented, then in reality it may not be an edge at all. Either way, it is a valid result because it reflects the positive relationship between percentage change and lesser degrees of fragmentation. Further, the more fragmented the edge of a patch, the more susceptible the patch is to change. As edges form the transition between 'heath' and 'non heath', this was to be expected, as the presence of available seed sources to facilitate the process of succession would be plentiful (Wilcove *et al.*, 1986 and Webb & Hopkins, 1984). Overall, it seems that preventing further fragmentation might play a key rôle in ensuring the survival of the remaining patches of dwarf shrub vegetation in Dorset. Indeed, Moore (1962) suggested that the stability of a habitat is, to a large extent, a function of its size. However, there was no such relationship between percentage change and fragment size, which implies that it is the internal fragmentation of a patch which is of most importance.

At the aggregated primary category level percentage change was significantly correlated with the area of invasive species in a patch. At the primary category level, scrub appeared the most likely invader of drier heaths whilst carr invaded wetter heaths. As stated previously, succession depends upon the availability of a seed source. In a study by Mitchell *et al.* (1997) aerial photographs indicated that a single plant of certain invasive species type in open heathlands was enough to facilitate the process of invasion from within a patch. Similarly, this analysis showed that areal extent of invasive species in a patch influenced the decline in area of dwarf shrub vegetation as a percentage of initial area. Unlike density, area does not reflect the degree of internal patch fragmentation. The relationship could imply that the process of succession was 'exponential'. Greater areas lead to greater percentage decreases which in turn lead to even greater areas of invasive species and further decreases in area of dwarf shrub vegetation. Indeed, the rate of succession virtually doubled between 1978 and

1987 (1%) and between 1987 and 1996 (2%). Further, percentage change was significantly correlated with the area of invasive species in the edge of a patch. The effect of invasive species in the edge of a patch indicated the process of succession from the periphery (outside) of a patch is also important. The greater the areal extent of invasive species in the edge of a patch, the greater the decline in area of dwarf shrub vegetation as a percentage of initial area. As Forman and Godron (1986) found, edges form the juxtaposition between dwarf shrub vegetation and an alternate environment. It is reasonable that edges are likely to be an important seed source facilitating the process of invasion. The areal extent of invasive species, be it woodland, scrub or carr (or all three in combination), indicates the degree of pressure a patch of dwarf shrub vegetation is under from succession. As area increases, the pressure from invasion increases, leading to a decline in area of dwarf shrub vegetation over time. Conversely, if there is no seed source supplying the necessary propagules to facilitate the process of succession (that is, if the area of dwarf shrub vegetation in a patch is large), invasion will not occur. This is where management can play its most effective rôle in the conservation of the dwarf shrub vegetation of Dorset.

Finally, percentage change was significantly correlated with the ratio of area of dwarf shrub vegetation type to invasive species type, again indicating that succession caused change, in particular, the ratio of dry heath to scrub, wet heath to scrub or carr and peatland to carr. It seemed that the greater the area of dwarf shrub vegetation relative to the area of invasive species type, the less the percentage change. Succession depends on the availability of a seed source: as the seed source declines with increasing area of dwarf shrub vegetation then the process of succession is slowed. The relationship between dry heath and wet heath and scrub indicated that scrub was the most likely invader of drier heaths with carr replacing scrub as the most likely invader of wetter heaths (wet heath and peatland). Many authors have illustrated the importance of edge effects in a fragmented environment (Webb & Hopkins, 1984; Forman & Godron, 1986; Wilcove *et al.*, 1986, Fagan *et al.*, 1999). Again, the hypothesised influence of edge effects appears correct. Percentage change was also significantly correlated with the ratio of dwarf shrub vegetation type to invasive species type in the edge of a patch reflecting the relationship between percentage change and area of invasive species outlined above. Succession from outside a patch (or a patch's periphery) caused as much change as succession from within a patch. The greater the area of dwarf shrub vegetation relative to the area of invasive species, the less the percentage change.

The patch-based analysis resulted in several interesting relationships. However, several other significant relationships could have resulted (Chapter 2, 2.4.1). In particular, percentage change was expected to be correlated with patch geometry (Diamond, 1975; Seagle, 1986; Rex & Malanson, 1990; LaGro, 1991 and Baskent & Jordan, 1995), context (Webb e*t al.*, 1984; Dunning *et al.*, 1992; Webb, 1992) and the area of dwarf shrub vegetation (Micthell *et al.*, 1997), but this was not so. For example, LaGro (1991) suggested that patch size and shape influenced several ecological processes. In particular, patch shape was suggested to influence change (Rex & Malanson, 1990 and Baskent & Jordan, 1995) as did the perimeter of a patch (Diamond, 1975). However, no such relationships were identified in this analysis. It had also been hypothesised that a patch's surroundings would exert an influence on change (Webb *et al.*, 1984; Dunning *et al.*, 1992 and Webb, 1992). However, the hypothesised relationship failed to account for the variation in percentage change. This was most likely the result of either data, sampling uncertainty and/or classification error. Further, a single remotely sensed image from 1984 was used to provide contextual information. Using a 1984 image to provide contextual information for patches dating from 1978 and 1987 meant the data may not have been an accurate representation of what surrounded each patch at the time of the surveys.

The small coefficients of determination may have resulted for several reasons. First, there may be a lack of variance in patch geometry. If most patches were similar geometrically, then one would not expect the relationship between change and patch geometry to be significant. However, the lack of variance may also have affected other variables. If patches were similar geometrically, then they are likely to contain similar areas of dwarf shrub vegetation. Again, if the area of dwarf shrub vegetation in many patches is similar, then the lack of a relationship between percentage change and area of dwarf shrub vegetation is not surprising. Second, many small patches made up of just one or two pixels may have biased the relationship. Patch geometry is unlikely to influence the behaviour of a patch formed by the amalgamation of one or two cells of dwarf shrub vegetation. However, an alternative analysis examined the relationship between percentage change in patches of varying sizes and the explanatory variables (see Appendix 5). The coefficients of determination did not increase. Third, noise in the data may have obscured the relationship. For example, the coarse numerical resolution of the data (the data being based on scores of between zero and three) must obscure certain relationships, as will sampling errors. That is, there is a lot of uncertainty in the data which must, in part, account for many of the small coefficients of determination achieved. In particular, a score of three indicated that between 50% and 100% of a pixel was covered by a certain vegetation type. Therefore, it is likely that many finer changes were obscured by the scale of the survey. Finally, many patches may not in reality be patches. Indeed, Lord and Norton (1990) suggested that patch attributes (for example patch geometry) are related to and are affected by the scale of fragmentation. The patches created for this analysis were based upon the loosest possible rules to form the least fragmented environment which could account for the lack of correlation between percentage change and patch geometry.

It seemed likely that the factors outlined above accounted for the small correlations between percentage change and patch area. However, they may also account for the lack of a significant relationship between percentage change and area of dwarf shrub vegetation. Patch area and area of dwarf shrub vegetation are intrinsically linked, as patches were created solely on the basis that pixels containing any area of dwarf shrub vegetation were amalgamated with similar neighbouring pixels.

This analysis suggests that change is most affected by area of invasive species. That is, invasion will not occur without the presence of a seed source. Therefore, the importance of area of invasive species far outweighs the importance of area of dwarf shrub vegetation (hence the small correlations between change and area), as the dwarf shrub vegetation cannot be invaded if invasive species are not present.

Overall, percentage change was influenced by the density of dwarf shrub vegetation in a patch (and in the edge), the area of invasive species in a patch (and in the edge), and the ratio of dwarf shrub vegetation to invasive species in a patch (and in the edge). Each of these relationships should be taken into consideration by heathland managers. Although the ecological literature indicates that such relationships should exist (for example, Diamond, 1975; Forman & Godron, 1986; Chapman *et al.*, 1989; Webb & Vermaat, 1990; Lavers & Haines-Young, 1993; Fagan *et al.*, 1999), the analysis confirms the belief that to protect the remaining dwarf shrub vegetation of Dorset, fragmentation must be prevented and invasive species removed.

7.3.2 Prediction

Several multiple regression equations resulted from the patch-based analysis, and these allow the prediction of percentage change in area of dwarf shrub vegetation types over time. Given that the maximum amount of variation in percentage change accounted for was 51%, these equations should be treated with caution. Further, as the data were logged interpretation is not straightforward. The relationships expressed in the predictive models are curvi-linear, that is, they are exponential.

At the aggregated primary category level, 17% of the variation in percentage change was accounted for by two variables. The density of dwarf shrub vegetation in the edge of a patch was most highly correlated with percentage change while the ratio of area of dwarf shrub vegetation to 'others' accounted for a significant portion of the residuals.

Log (percentage change) = 4.2 + 1.1 log (density of dwarf shrub vegetation in the edge) + 0.3 log (ratio of area of dwarf shrub vegetation to 'others').

At the primary category level, four explanatory variables accounted for 32% of the variation in percentage change in area of dry heath between 1978 and 1987.

Log (percentage change) = 0.7 + 0.3 log (area of carr in the edge of a patch) + 0.1 log (area of scrub in the edge of a patch) + 1.7 log (ratio of density of dry heath to humid heath) + 0.1 log (ratio of area of dry heath to carr in the edge of a patch).

If the area of carr in the edge of a patch, the area of scrub in the edge of a patch, the ratio of density of dry heath to humid heath and the ratio of density of dry heath to carr in the edge of a patch are all known, then percentage change can be predicted. However, the equation accounted for only a third of the variation in percentage change. Percentage change in area of dry heath between 1987 and 1996 was not significantly correlated with a single variable. Percentage change in area of humid heath between 1978 and 1987 was significantly correlated with three variables which together accounted for 23% of the variation in percentage change. The density of humid heath in the edge of a patch accounted for most variation in percentage change. When this variable was held constant, the density of scrub in the edge of a patch was significantly correlated with percentage change. The ratio of density of humid heath to scrub in the edge of a patch accounted for a significant amount of the remaining residuals. It appears that edge effects play an important part in causing change in area of humid heath, particularly, the area of both humid heath and scrub in the edge of a patch. The multiple regression equation is as follows:

Log (percentage change) = 6.2 + 0.63 log (density of humid heath in the edge of a patch) + -9.6 log (density of scrub in the edge of a patch) + -3.4 log (ratio of density of humid heath to scrub in the edge of a patch).

Density of humid heath accounted for a significant portion of the variation in percentage change, density of scrub in the edge accounted for a significant portion of the residuals and the ratio of density of humid heath to scrub in the edge accounted for a significant amount of the remainder. Similarly, percentage change in area of humid heath between 1987 and 1996 was correlated with four variables which accounted for 35% of the variation in percentage change. Therefore, the multiple regression equation could be used for prediction. The multiple regression equation is as follows:

Log (percentage change) = 0.7 + 0.3 log (area of carr in the edge of a patch) + 0.1 log (area of scrub in the edge of a patch) + 1.7 log (ratio of density of dry heath to humid heath) + 0.1 log (ratio of area of dry heath to carr in the edge of a patch).

Consistently, density of humid heath (in a patch or the edge) accounted for most variation in percentage change in area of humid heath. The main difference between the multiple regression results to examine the influences on percentage change in area of humid heath between 1978 and 1987 and between 1987 and 1996 was that scrub influenced change between 1978 and 1987 whereas scrub, carr and woodland all influenced change between 1987 and 1996.

Percentage change in area of peatland between 1978 and 1987 was correlated with two variables, which in combination accounted for 14% of the variation in percentage change. The ratio of area of peatland to scrub in the edge of a patch accounted for most variation while the ratio of area of peatland to carr in a patch accounted for a significant amount of the residuals. However, percentage change in area of peatland between 1987 and 1996 was correlated with three variables, which together accounted for 51% of the variation in percentage change. Again, the ratio of area of peatland to carr was significant. When its influence was removed, the density of peatland in the edge of a patch accounted for a significant amount of the variation in percentage change. The perimeter of a patch accounted for a significant amount of the remainder. This multiple regression model provided the most accurate predictor of change because of the high coefficient of determination. The large coefficient of determination probably resulted because peatland is less likely to be built upon or converted to agriculture than a drier dwarf shrub vegetation type.

Log (percentage change) = 0.7 + 0.3 log (area of carr in the edge of a patch) + 0.1 log (area of scrub in the edge of a patch) + 1.7 log (ratio of density of dry heath to humid heath) + 0.1 log (ratio of area of dry heath to carr in the edge of a patch).

Overall, the percentage change at the primary category level between 1987 and 1996 produced more accurate predictive models than those for percentage change between 1978 and 1987 at the primary catgeory level. However, in all cases, the coefficients of determination were small and, therefore, the predictive power of the equations should be questioned.

7.4 Pixel-based approach

Percentage change between 1978 and 1987 and between 1987 and 1996 was significantly correlated with just a few variables with very small coefficients of determination. The explanatory variables were chosen because they encompassed factors likely to influence succession and, therefore, would influence percentage change. As succession influenced percentage change at a patch level then it should have influenced change at a pixel level. In particular, percentage change was hypothesised to be significantly correlated with the distance a pixel lay from the edge. Although the importance of edge effects was shown by the patch-based analysis and by other authors (Webb & Hopkins, 1984; Wilcove *et al.*, 1996; Forman & Godron, 1986; Lavers & Haines-Young, 1993; Fagan *et al.*, 1999), distance from the edge did not appear to influence percentage change in a pixel.

The hypothesised relationship between percentage change and density of invasive species surrounding a pixel was not significant. The patch-based analysis illustrated clearly the relationship between percentage change and invasive species and previous work has shown the importance of proximity to a seed source (Mitchell *et al*, 1997) and the importance of context (Webb *et al.*, 1984; Dunning *et al.*, 1992; Webb, 1992). However, at the pixel level, there were no such significant relationships. The lack of a significant relationship between percentage change and the area of invasive species in a pixel may have been the result of the scale of the analysis. Relative to the area of dwarf shrub vegetation in a pixel, the area of invasive species is never likely to be very large because the surveys were biased towards dwarf shrub vegetation. Further, because the pixel scale is a human-imposed scale, it is likely that the area of invasive species in a pixel is an inadequate measure of the pressure from succession.

Overall, there was no apparent reason for the lack of significant relationships. Based on current understanding (Chapter 2, section 2.4.1) the choice of explanatory variables appeared justified. Perhaps, the poor relationships arose as a result of the scale of the analysis. Both the patch and pixel analyses encompassed both the largest and smallest possible scales of an analysis of change in a fragmented environment. That is, the patches were created using the loosest possible rules producing the least fragmented environment, whereas the pixel-based approach reduced the analysis down to the smallest possible scale. A 200 m by 200 m square is an arbitrary divide and it is unlikely that dwarf shrub vegetation functions on such a human-imposed scale. However, such a scale was chosen originally because it was expected to be small enough to detect vegetation change (Chapman *et al.*, 1989). This invites the question, were Chapman *et al.* (1989) correct in their choice of a 200 m by 200 m scale for the Dorset Heathland Surveys? Although it should be taken into consideration that Chapman (1975) devised the survey with alternative aims to this analysis. Perhaps the coefficients of determination would have been increased by examining percentage change at a level some way between a patch and pixel or at an even finer scale. If the scale of the Dorset Heathland Survey were altered and the numerical resolution of the data increased (from the current scale of between zero and three) then perhaps the correlations would also increase. However, this research is unable to provide any indication as to the best scale for a survey of this kind.

An alternative reason for the lack of significant results from the pixel-based analysis is data uncertainties. Inaccuracies in data collection were likely both as a result of score estimates and in the correct location of pixels for surveying. A scoring system of between zero and three was used to account for the presence or absence of land cover (and land use) types. Thus scoring was a subjective process. Further, the exact location of each vegetation type in a pixel was unknown. At a patch level a smoothing process takes place across the patches as a cluster of pixels were examined in combination. Smoothing increases the signal-to-noise ratio for patches. However, there is no such smoothing process at the pixel level.

Perhaps the lack of correlations between percentage change and the pixel-based explanatory variables occurred because the null hypotheses were true. Maybe succession was not influenced by the spatial characteristics of species composition in a pixel, and edge effects and context do not affect the process of change. If there is a ubiquitous seedbank, or more likely, a ubiquitous seed rain then succession would not be a spatial process. That is, if *Pinus spp*. seeds can disperse evenly across an entire patch then succession is not necessarily a spatial process for that patch. Further, as the dwarf shrub vegetation of Dorset is so fragmented already, perhaps there is no patch remaining which is large enough to avoid such ubiquitous seed rain. Perhaps, every patch, irrespective of size, contains an areal extent of invasive species large enough to facilitate seed rain into every part of that patch. If this is indeed the case then management in the form of the complete eradication of invasive species is the only possible preventative measure.

Such ubiquity of seed rain is unlikely and it also seems unlikely that succession is not influenced by the spatial characteristics of species composition in a pixel, and edge effects and context do not affect the process of change given how the process of succession in a fragmented environment takes place (Chapter 2, 2.3.2). The dwarf shrub vegetation of Dorset is a plagio-climax community: in the absence of factors arresting succession they will revert to woodland. Succession is a directional temporal change in species composition or relative abundances and is a central theme in plant community ecology (Glen-Lewin *et al.*, 1992 and Miles & Walton, 1993). Succession depends upon the presence of a seed source (Mitchell *et al.*, 1997). Therefore, the presence of a seed source is enough to facilitate the process of succession. Further, from the literature it was clear that edge effects in the form of presence of invasive species (Webb & Hopkins, 1984; Wilcove *et al.*, 1996; Forman & Godron, 1986; Lavers & Haines-Young, 1993; Fagan *et al.*, 1999) and context in the form of area of invasive species (Webb *et al.*, 1984; Dunning *et al.*, 1992; Webb, 1992) consistently influenced change. Therefore, it seems highly unlikely that the null hypothesis can be accepted to account for the lack of significant relationships resulting from the pixel-based analysis of percentage change.

The use of regression may not have been appropriate. However, regression is a commonly used method in ecology to model change (for example, Osborne and Wiley, 1988; Broschart *et al.*, 1989; Johnston *et al.*, 1992; Moore *et al.*, 1993; Sarre *et al.*, 1995; Abramsky *et al.*, 1986; Aitkin & Francis, 1982; Philippi, 1993 and Trexler & Travis, 1993; Schumaker, 1996;

Matter, 1997, to name but a few). Further, it allows prediction and prediction is an important tool to the ecologist. For example, predicting what is most vulnerable following habitat fragmentation (as in the case of the heathlands of Dorset) is one of the most pressing problems facing conservation biologists (Sarre *et al.,* 1995). Other types of model, such as cellular automata, could have been used. However, to build such a model the exact causes of change need to be understood in order to parameterize the model. Further, such models provide no insight into the processes of change.

Overall, the pixel-based analysis did not produce any usable models. The reasons behind the lack of significant relationships were not clear but it may be a simple question of scale.

7.5 A comparison of the patch- and pixel-based analyses

The patch-based analysis produced several usable models. However, the pixel-based analysis did not. This does not necessarily mean that change did not occurr at a pixel level. Rather, it may be that uncertainties in the data obscured the relationships identified at the patch level.

Percentage change in a patch was influenced by the density of dwarf shrub vegetation in a patch (and in the edge), the area of invasive species in a patch (and in the edge), and the ratio of dwarf shrub vegetation to invasive species in a patch (and in the edge). Further, at the patch level, percentage change was consistently significantly correlated with area of dwarf shrub vegetation although the relationship was the inverse of that hypothesised. The pixel-based analysis identified a positive relationship between percentage change and the area of dwarf shrub vegetation (or dwarf shrub vegetation type) in a pixel, although the coefficients of determination were small.

The inverse relationship between percentage change and area of dwarf shrub vegetation (at the primary category level) probably resulted because if the area of, for example, humid heath in a patch was large, then edge effects were likely to influence change. However, if a patch contained a small area of humid heath, then it is probable that that area of humid heath would be protected by the areas of other dwarf shrub vegetation types which surrounded it. The opposite is true at the pixel level. A larger area of dwarf shrub vegetation would be less susceptible to change than a smaller area simply because a larger area of dwarf shrub vegetation implies less invasive species at the pixel scale.

In all, the pixel-based analysis was less fruitful than the patch-based analysis. This has important implications for model building and for the parameterization of other models such as cellular automata.

7.6 The influence of management on change in a patch and pixel

Initially, the relationship between percentage change (increases) and management at a patch level was analysed. The proportion of a patch managed using pine clearance, rhododendron clearance, scrub clearance and bracken spraying all proved significant for certain target variables. It was interesting that the significant relationships only occurred at a primary category level. Percentage change in area of wet heath was significantly correlated with bracken spraying. When the influence of bracken spraying was held constant, percentage change was significantly correlated with pine clearance. In all 20% of the variation in percentage change was accounted for. Percentage change in peatland was significantly correlated with the proportion of a patch cleared of pine, scrub and rhododendron. When the influence of rhododendron clearance was held constant, percentage change was significantly correlated with pine clearance. Further, when the influence of pine clearance was held constant, percentage change was significantly correlated with scrub clearance. In all, 24% of the variation in percentage change was accounted for. It appeared that certain management caused the area of certain dwarf shrub vegetation to increase. However, most of the analyses produced no significant correlations.

Percentage decreases in area of dwarf shrub vegetation were also examined. Percentage decreases in area of peatland was significantly correlated with three variables. When the influence of pine clearance was held constant, percentage change was significantly correlated with managed burning. Further, when the influence of managed burning was held constant, percentage change was significantly correlated with the proportion of a patch grazed. In all, 21% of the variation in percentage change was accounted for. Management aims to maintain dwarf shrub vegetation (Webb, 1990) but this analysis indicated management activities not only maintain the area of certain dwarf shrub vegetation types by arresting succession, but also resulted in increased areal extent of some dwarf shrub vegetation types. This has important implications for heathland managers. However, it is also important to remember that the management records upon which the analysis was based, were mostly hand drawn maps which were often difficult to interpret and so the data were prone to error, particularly through mis-registration.

The relationships between percentage change and management (and management type) in a pixel were examined. The coefficients of determination reflected those from the previous pixel-based analysis of percentage decreases in area of dwarf shrub vegetation. No variable was significantly correlated with percentage change in area of dwarf shrub vegetation in a pixel. It was reasonable to expect that the effect of management would have been felt more acutely at the pixel level rather than at the patch level. However, this was not so. The most obvious reason for the absence of significant relationships was that the exact area of a pixel managed was unknown. Examining the effect of management in a single pixel was not likely to produce significant relationships. Most pixels were not managed and of those that were, only a proportion of the pixel may have been managed.

In the patch-based analysis managed pixels were amalgamated, strengthening the relationships. The relationships were further strengthened because proportion rather than area of a patch managed was used as the explanatory variable, thereby, taking into account the vast areas of patches which remained unmanaged. Perhaps with hindsight, the small coefficients of determination between percentage change and management are not surprising. However, as in the analysis of percentage decreases in area of dwarf shrub vegetation, it may also be a question of scale, the pixel being too large to detect natural processes of change. Throughout the analysis percentage change was not correlated with management overall. The lack of a significant relationship between percentage change and management probably resulted because management is never evenly applied over a patch or pixel. Overall, management appeared to arrest the process of succession at a patch-level in a few cases. Indeed, it appeared to account for a decline in percentage decreases and in some instances even resulted in percentage increases in area of dwarf shrub vegetation

7.7 Comparison with other analyses

It is important to remember when making comparative estimates of change to define the term heathland. For this analysis it was defined as a combination of dry, wet, humid heath and peatland forming what was known as dwarf shrub vegetation. This definition reflected (for the most part) that used by Webb and Haskins (1980), Chapman *et al.* (1989), Webb (1990), Webb (1992) and Rose *et al.* (in press). There was one main difference between these analyses and the current analysis, this was the way that patches were formed. Webb and Haskins (1980) created patches based purely on physical isolation. Every area of heath which was not in contact with any other was considered separately. For example, when a heathland fragment was divided by an unmetalled road or disused railway, it was considered a single fragment. However, heathland divided by a metalled road or used railway was considered as two separate fragments. This approach produced 768 separate fragments. Chapman et al., (1989) amalgamated pixels with adjoining sides but pixels on the diagonals were only included when they were made up of at least seventy five percent heathland or its associated vegetation types. This process produced 141 patches in 1978. Webb (1990) used a similar rule to Chapman *et al.* (1989) which resulted in 135 fragments. Finally, Rose *et al.* (in press) grouped pixels with some dwarf shrub heath or acid grassland based on the rules set out by Chapman *et al.* (1989). This resulted in 137 patches in 1978, 142 in 1987 and 151 in 1996. By amalgamating pixels (both adjacent pixels and pixels along the diagonals) based on whether or not they contained any area of dry heath, wet heath, humid heath or peatland, this analysis produced 116 patches in 1978, a difference of twenty one patches based on the Rose *et al.* (in press) rule and a difference of twenty five patches based on Chapman *et al.* (1989) rule. This approach to patch-building was adopted because this analysis was concerned with dwarf shrub vegetation (that is, dry heath, humid heath, wet heath and peatland alone) while the other analyses were interested in heathland. Despite the rather different approach to patch formation, the results did not differ substantially.

The present analysis produced a less fragmented dwarf shrub vegetation environment than the other analyses. When the area of dwarf shrub vegetation in a patch was mapped (see Chapter 3, Fig. 3.8) it reflected the kind of fragmented environment expected. Larger patches had core areas made almost entirely of dwarf shrub vegetation while the edge pixels contained little dwarf shrub vegetation (Webb & Hopkins, 1984 and Fagan *et al.*, 1999). That is, the area of dwarf shrub vegetation lessened with increasing proximity to the edge. Further, density of dwarf shrub vegetation was included as an explanatory variable in the analysis. Density took into account the degree of fragmentation of the area of dwarf shrub vegetation in a patch. Therefore, if the method of creating patches for this analysis was a less accurate representation of reality than those produced by Webb (1990) and Chapman *et al.* (1989), the inclusion of a surrogate variable for fragmentation took this into account.

As mentioned previously, several other analyses of change in area of dwarf shrub vegetation in lowland heathlands of Dorset have been carried out, including Webb and Haskins (1980), Chapman *et al.* (1989), Webb (1990), Webb (1992) and Rose *et al.* (in press). These analyses were also based upon the Dorset Heathland Survey data. However, while this analysis aimed to model change in relation to the spatial structure of the dwarf shrub vegetation of Dorset, the other analyses aimed to examine gross areal change over time. Therefore, the analyses are not directly comparable. However, an areal analysis of change was carried out prior to model building and the results of this analysis are readily comparable to the previous analyses (Table 7.1). Webb and Haskins (1980), included some scrub on occasion and Rose *et al.* (in press) included some scrub and acid grassland in their definition of 'heathland' which may account for the variation in results. Change was calculated based on the same number of pixels in 1978 and 1987 and in 1987 and 1996. These analyses produced relatively similar results (Table 7.1).

Of most interest was the isolation of the same processes of change identified in each of these analyses. Webb (1990) identified two factors which caused change. First, there were direct losses due to land use change, which resulted in a loss of 330 ha of heathland. In particular, the expansion of farmland, forestry and urban industrial development. Second, the process of succession caused further losses. The area of scrub and woodland increased by 15% between 1978 and 1987 according to Webb's calculations (1990). Rose *et al.* (in press) noted similar processes of change. 240 ha were lost as a result of land use change and 141 ha were lost due to succession. The authors found the same processes caused change between 1987 and 1996. They calculated that the area lost to land use change between 1987 and 1996 was 140 ha (including forestry plantations) and a further loss of 140 ha resulted from invasion of scrub, carr and woodland. These results reflected the processes of change identified by this analysis. Between 1978 and 1987 land use change was the dominant process of change. However, succession did result in some losses. This changed between 1987 and 1996 with succession replacing land use change as the dominant process causing the area of dwarf shrub vegetation to decline. However, land use change did continue to cause heathland change. This analysis found that the area of dwarf shrub vegetation declined by 5.3 km^2 between 1978 and 1987 while land use change increased by 4.2 km^2 and invasive species by 1.1 km^2. Between 1987 and 1996 the area of dwarf shrub vegetation was still in decline. It decreased by 7.6 km^2, while the area of land use change decreased by 8.2 km^2. However, the area of invasive species increased by 13.1 km^2. Again, this analysis illustrated the decline in the process of land use change and the rapid increase in the area of invasive species.

Table 7.1 A comparison between the analyses of change in area of heathland in Dorset, 1978 - 1996

	Total area of heath in 1978 (ha)	**Total area of heath in 1987 (ha)**	**Total area of heath in 1996 (ha)**	**Percentage change 1978 - 1987 (%)**	**Percentage change 1987 - 1996 (%)**
Webb & Haskins, (1980)	5,832	-	-	-	-
Chapman *et al.*, (1989)	5,507	-	-	-	-
Webb (1990)	-	5,141	-	- 5.0	-
Rose *et al.*, (in press)	5,453*	5,065*	4,720*	- 7.1*	- 7.0*
This research	5,510	4,978	4,222	- 10.0	- 15.0

*calculated by combining the areal extents of dry heath, wet heath, humid heath and peatland based on the same 3,110 pixels from 1978 as calculated by Rose *et al.* (in press) to make the figures comparable.

7.8 Conclusions

The dwarf shrub vegetation of Dorset is in decline. Land use change and succession were the main causes of this decline. The effect of land use change has been removed, but the process of succession appeared unabated despite the best efforts of heathland managers between 1987 and 1996 (Auld *et al.*, 1992; Woodrow *et al.*, 1996). Indeed the rate of succession was calculated to be 1% per annum between 1978 and 1987 increasing to 2% between 1987 and 1996 (this analysis and Rose *et al.*, in press). This analysis has used a statistical modelling technique to provide insight into the causes of percentage change in area of dwarf shrub vegetation (and dwarf shrub vegetation type) over time. Modelling indicated that for the dwarf shrub vegetation to survive, further fragmentation must be prevented. Fragmentation can most easily be controlled by considerably reducing the areal extent of invasive species across all Dorset.

CHAPTER 8

CONCLUSIONS

8.1 Summary

Much of the dwarf shrub vegetation in Dorset has been lost over the last century and a half. The dwarf shrub vegetation that has survived has been considerably fragmented and this has increased the likelihood of further losses both of dwarf shrub vegetation and the fauna it supports (Moore, 1962). Haskins (1978) calculated from Isaac Taylor's maps of Hampshire and Dorset that 39,960 ha of heathland existed in Dorset between 1759 and 1765. Today 4,222 ha remain (Chapter 4, 4.3.2). It is because so little of the dwarf shrub vegetation of Dorset remains and because of the rare communities and species they support that they are now a top priority for habitat conservation in Britain (Biodiversity Steering Group, 1995). Therefore, there was (and still is) an urgent need to quantify the problem of fragmentation by developing models of change. Such models will prove invaluable to heathland managers. Therefore, the aim of this research was to model the spatial dynamics of the dwarf shrub vegetation of Dorset.

Many analyses of change have been carried out previously (Webb and Haskins, 1980; Chapman *et al.*, 1989; Webb, 1990; Webb, 1992 and Rose *et al.*, in press) but this research encompassed the first attempt to build models of change. Further, it was one of the first attempts to model succession as a spatial process (Rejmánek, 1995; Holt *et al.*, 1995). A GIS, remote sensing and regression were used to build models of change in the dwarf shrub vegetation of Dorset. Four main processes were identified as causal factors behind the decline in area of dwarf shrub vegetation between 1978 and 1987 and between 1987 and 1996. These were land use change, succession, management and transitions between dwarf shrub vegetation types. Anthropogenic effects were not predictable from present dwarf shrub vegetation status. Therefore, natural ecological change resulting from succession was the focus of this analysis using regression. The relationship between percentage change and a series of explanatory variables facilitated the production of models of change. Further, explanatory variables were chosen based on their expected influence on the process of succession in a fragmented dwarf shrub vegetation environment. Change was examined at a patch and a pixel level. Ecological forces operate at different spatial and temporal scales, so that changes may themselves be patchy (Dunn *et al.*, 1991). Therefore, within a single landscape, different patches (or pixels) change at different rates creating a complex pattern of change (di Castri & Hadley, 1988). Taking a patch and a pixel approach was an attempt to take into account the fact that change occurred at different spatial scales. Further, change was examined at two levels, an aggregated primary category level (change in the total area of dwarf shrub vegetation was examined) and at a primary category level (change in area of dry heath, wet heath, humid heath and peatland were examined).

The patch-based model indicated that three processes were likely to cause a decline in area of dwarf shrub vegetation over time. First, density (believed to indicate fragmentation) of the remaining dwarf shrub vegetation in a patch (and in the edge of a patch). Second, the areal extent of invasive species in a patch. Third, the area of dwarf shrub vegetation relative to the area of invasive species in a patch (and in the edge of a patch). Therefore, each of the three influenced the process of succession. In all, if fragmentation can be prevented by reducing the areal extent of invasive species in a patch then the dwarf shrub vegetation of Dorset should remain intact. Further, the analysis indicated that management not only arrested change but could result in increases in area of dwarf shrub vegetation over time. The pixel-based analysis failed to result in any significant relationships.

8.2 Future Research

This research produced some significant relationships between percentage change and factors related to the process of succession. However, the coefficients of determination were relatively small. At the patch-level this appeared to be a function of the effect of land use change and uncertainties associated with the data. Future research will involve further investigation into the effect of land use change. Further attempts at isolating its effect and removing the noise it creates will be made, thereby strengthening the signal resulting from the relationship between percentage change and the explanatory variables.

The pixel-based analysis produced no significant results. Change may well occur at a sub-patch level but at a super-pixel level. The pixel-based analysis moved from one extreme (patches were created using the loosest possible criteria resulting in the least fragmented environment) to another (the pixel-based analysis was the smallest possible scale based on the data). In the future, patches will be created using a variety of rules and the analyses repeated with the aim of isolating the best scale for the analysis of change. Patches can be created simply and efficiently using the GIS.

Finally, this analysis illustrated that change occurred because of two main ecological processes: succession and transitions between dwarf shrub vegetation types. The transitions between dwarf shrub vegetation types were not examined in any detail in this analysis. Future work will involve isolating the factors most likely to cause transitions between dwarf shrub vegetation types and an attempt to model change will be made, thus providing further insight into the spatial dynamics of the dwarf shrub vegetation of Dorset.

8.3 Conclusion

The heathlands of Dorset are in decline and further fragmentation must be prevented. The patch-based analysis produced several significant results. In particular, consistently, percentage change was significantly correlated with the density of dwarf shrub vegetation in a patch (or in the edge of a patch). As the area of dwarf shrub vegetation became more fragmented, percentage change increased. Percentage change was also significantly correlated with the area of invasive species in a patch. As area increased, percentage change increased. Further, percentage change was significantly correlated with the ratio of area of dwarf shrub vegetation to invasive species in a patch (or in the edge of a patch). As the area of dwarf shrub vegetation increased relative to the area of invasive species, percentage change decreased. However, the relationship between percentage change and the area of dwarf shrub vegetation in a patch was not significant. The lack of a significant relationship between these two variables may have been caused by several factors, including a low signal-to-noise ratio and the method used to create patches. In all, the patch-based analysis indicated that the prevention of further fragmentation through the removal of invasive species is the key to the heathlands survival.

The pixel-based analysis was unfruitful. Percentage change was not significantly correlated with a single variable. The most likely reasons for the lack of significant relations at the pixel level was the scale of the analysis and the uncertainties associated with the data. The low signal-to-noise ratio was the most likely cause of the small coefficients of determination.

The analysis of management provided some insight into the influence of management on change (both increases and decreases) in area of dwarf shrub vegetation over time. When percentage increases were examined, only percentage change in area of wet heath and peatland were significantly correlated with management at a patch level. Percentage change in area of wet heath (increases) was significantly correlated with the proportion of a patch managed using bracken spraying and pine clearance. Percentage change in area of peatland (increases) was significantly correlated with the proportion of a patch managed by rhododendron clearance, pine clearance and scrub clearance. Further, percentage change in area of peatland (decreases) was also significantly correlated with the proportion of a patch cleared of pine and managed using controlled burning and grazing. The pixel-based analysis failed to produce any significant relationships. Overall, despite considerable effort by heathland managers, management does not appear to have a great effect.

I hope that these findings will provide a useful insight for heathland managers and will aid in the prevention of further losses of the dwarf shrub vegetation of Dorset.

Appendix 1

Image correction

The intent of image rectification and restoration is to correct image data for distortions or degradations that stem from the image acquisition process (Lillesand and Kiefer, 1994). The removal of effects (from a remotely sensed image), whose magnitude is known, for example, the curvature of the Earth, is known as image restoration. A remotely sensed image can be corrected by suppressing the effects whose magnitudes are not known, like atmospheric scatter and sensor wobble (Andrews, 1974).

Raw digital images usually contain geometric distortions so significant that they cannot be used as maps. The sources of these distortions range from variations in the altitude, attitude, and velocity of the sensor platform, to factors such as panoramic distortion, Earth curvature, atmospheric refraction and nonlinearities in the sensors' field-of-view (FOV) (Lillesand and Kiefer, 1994). The aim of geometric correction is to make an image conform to a pre-arranged scheme. This can involve a large number of image manipulations, like the correction of predictive sampling errors that arise from changes in aircraft or satellite altitude, or the alteration of image projection to produce a stereo pair of images (Batson *et al.*, 1976) or the distortion of an image to make a fit onto another image or map (Moik, 1980). These geometric corrections can be achieved in a number of ways. The location of lines or pixels may be altered in the image or the image completely resampled (Naraghi *et al.,* 1983). Images collected by satellites with linear array sensors are systematically distorted as the Earth rotates. This effect can be removed by rectifying each scanline during image formation (Curran, 1985).

Image resampling involves the reformation of an image onto a new base by using features common to both the image and the new base (Bernstein, 1976). These common features are known as ground control points. They are chosen as they are in sharp contrast to their surroundings. Ground control points are located on an image by their x and y co-ordinates, and on the new base by their latitudinal and longitudinal co-ordinates The functional relationships (f_1 and f_2) between x and y and the latitude and longitude are determined by least squares regression :

$$x = f_1\ (\mathrm{X}, \mathrm{Y})$$
$$y = f_2\ (\mathrm{X}, \mathrm{Y})$$

where (x,y) = distorted image co-ordinates

(X,Y) = correct (map) co-ordinates

$f1, f2$ = transformation functions

To geometrically transfer an image, using these equations, there are four stages to proceed through:

1. A geometrically correct geographical grid is defined in terms of latitude and longitude.
2. The computer proceeds through each cell in the geographical grid transforming the latitudinal and longitudinal co-ordinates to x and y co-ordinates which become the new address for an image pixel.
3. The computer visits this address in the image and transfers the appropriate digital number from the nearest pixel (for the nearest neighbour method only) to this address and its new home in the geographical grid.
4. This process is repeated until the grid is full. Once full, the image has been geometrically corrected.

Appendix 2

An alternative response variable

Initially, the response variable was areal change in dwarf shrub vegetation. It is obvious that areal change will always be highly correlated with area and therefore, it was not surprising that the multiple regression produced several significant relationships (for example, Table 1). Multiple regression can be used to take into account, the high correlation between change in area and area of heath (for example) by holding area constant and determining whether another variable is significantly related with the residuals. Three significant variables explained sixty three of the variation in change in area of heath between 1978 and 1987 (Table 1). However, sixty one of this variation was explained by the area of heath in the edge of a patch. The multiple regression results when percentage change in area of dwarf shrub vegetation in a patch was used as the response variable can be seen in Table 2 below. The correlation coefficient fell considerably when percentage change rather than areal change was used as the response variable, because areal change and area are highly correlated. Therefore, percentage change was the obvious choice of response variable.

Table 1. Multiple regression results for patch-based aggregated primary categories, 1978

Log of change in area of heath versus the log of patch-based explanatory variables	*df*	*p*	r^2
Area of heath in the edge	1, 81	0	0.61
+ Area of 'others'	2, 80	0	0.02
+ Area of 'others' in the edge	3, 79	0	0.01

Table 2. Multiple regression results for patch-based aggregated primary categories, 1978

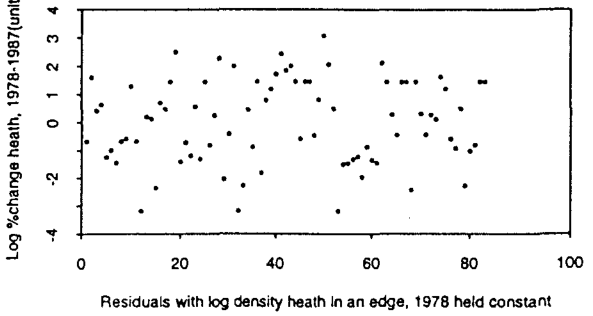
Log of percentage change in area of heath versus log of patch-based explanatory variables	*df*	*p*	r^2
Area of heath in the edge	1, 81	0.0002	0.15
+ Area of heath : 'others'	2, 80	0.0012	0.02

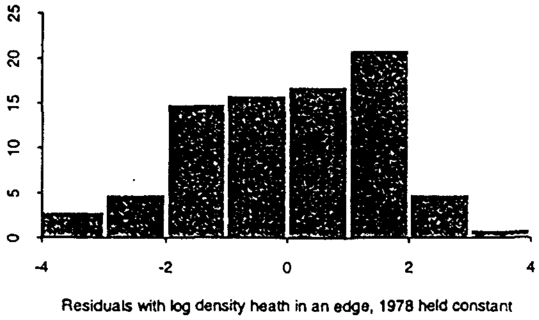
Appendix 3

Testing the residuals for normality

Many of the methods of statistics depend on the assumption that the variables under consideration are normally distributed. The meaning of a normal distribution may be most easily understood by considering certain graphs such as the histogram. A normal distribution is, however, an ideal distribution, the ideal being symmetrical and bell-shaped. In regression analysis the residuals should be normally distributed, not the actual variables. The residuals can be defined as the difference between the predicted and the observed values .

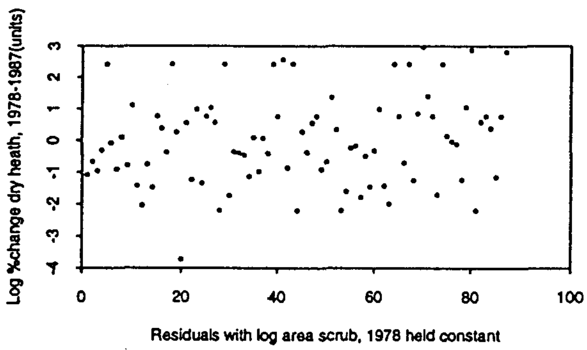
The residuals of the most significant variable at the aggregated primary category level (at the 95% confidence interval) were plotted. Percentage change in area of dwarf shrub vegetation between 1978 and 1987 was most highly correlated with density of dwarf shrub vegetation in the edge of a patch. The density of dwarf shrub vegetation in the edge of a patch was held constant and the residuals plotted as both a scatterplot and a histogram (see below). The residuals indicate the variation that is not explained by the logged density of dwarf shrub vegetation in the edge of a patch. Therefore, the residuals represent other influences on the log of percentage change in area of dwarf shrub vegetation over time. Good prediction requires that the residuals be as small as possible. If prediction is good, the line will closely fit the data. It is clear that the residuals are not small, the linear model (Chapter 4, Fig. 4.31) indicated as much, as did the small r^2 (0.15). The histogram indicates that the residuals are normally distributed, that is they approximate a bell-shape. Therefore, the regression is a valid one.

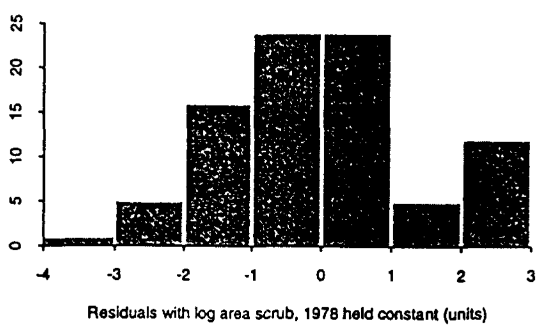




The residuals when the logged density of dwarf shrub vegetation in the edge of a patch, 1978 was held constant.

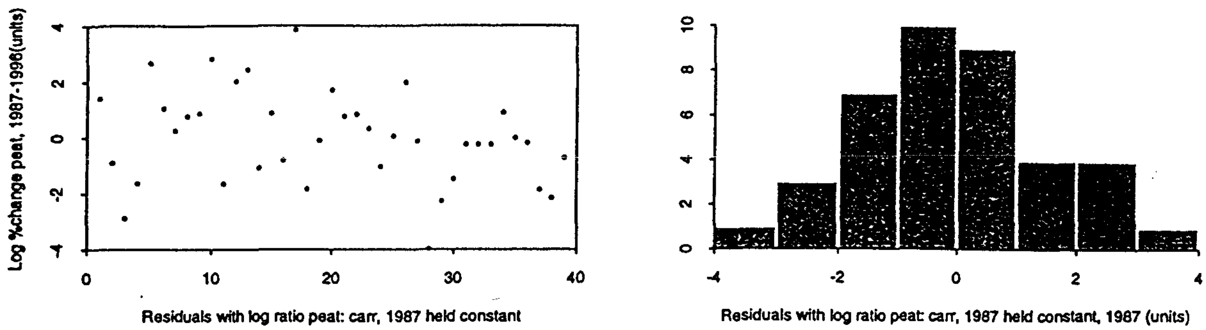
The residuals of the most variable most highly correlated with percentage change in area of dwarf shrub vegetation type, that is at the primary category level, between 1978 and 1987 (at the 95% confidence interval) were plotted. The highest correlation coefficient resulted when percentage change was regressed against the are of scrub in a patch. The area of scrub in a patch was held constant and the residuals plotted as both a scatterplot and a histogram (see below). Again, the residuals are not small, the linear model (Fig. 4.35) also indicated as much as did the small correlation coefficient (r^2 = 0.23). Therefore, the model is not a good predictor of percentage change in the area of dry heath between 1978 and 1987. It is clear from the histogram that the residuals are normally distributed, that is they approximate a bell-shape. Therefore, the regression is a valid one.





The residuals when the logged area of scrub in a patch, 1978 was held constant.

The residuals of the variable most highly correlated with percentage change in area of a dwarf shrub vegetation type at the primary category level (at the 95% confidence interval) were plotted. Percentage change in area of peatland was most highly correlated with the ratio of peatland to carr in a patch was held constant and the residuals plotted as both a scatterplot and a histogram (see below). Again, the residuals are not small, the linear model (Chapter 4, Fig. 4.55) indicated as much, as did the small correlation coefficient (r^2 = 0.36). Therefore, the model is not a good predictor of percentage change in the area of peatland between 1978 and 1987, however, it is the best model to date. It is clear from the histogram that the residuals are normally distributed, that is they approximate a bell-shape. Therefore, the regression is a valid one.



The residuals when the logged ratio of area of peatland to carr in a patch, 1987 was held constant.

Appendix 4

Controlling for the effect of land use change

When it became clear that changes in land use played an important rôle in percentage change, an alternate analysis was carried out. As land use change obscured the spatial process of succession and weakened the analysis because changing land use is not a spatial process, it is not dependent on patch size. Initially, patches where the area of 'others' increased by greater than 10% were removed thereby erasing some of the effect of land use change. Simple regression was then carried out with the aim of improving the relationship between percentage change in area of heath in the remaining patches and the explanatory variables. However, the correlations did not increase. An alternate threshold was applied, with patches in which the area of 'others' rose by over 5% were removed. Simple regression was again carried out. Again, the correlation coefficients were no higher than those from the original analysis. This led to a second analysis.

An alternate response variable was used: percentage change in area of invasive species. Again, simple regression was carried out with the aim of trying to isolate the influences on percentage change in heath, the regression analysis aimed to isolate the causal factors behind the changes in invasive species over time. If percentage change in area of dwarf shrub vegetation could not adequately be explained because changes in land use were obscuring the relationship between percentage change and succession, then using an alternate response variable may hold the answer. Percentage change in area of invasive species was used as an alternative response variable allowing for the effect of changes in land use and preventing the effect of succession being hidden by 'noise'. Feature space plots previously indicated that change in area of invasive species resulted from decreases in area of dwarf shrub vegetation, not from land use change. Despite the use of the alternative response variable, the correlation coefficients did not increase. Therefore, it did not appear possible to remove the obvious effect of the influence of land use change. Land use changes serve to obscure relationships but not in any systematic way.

Appendix 5

Investigating the effect of patch size

In theory, different patterns of change could exist for different patch sizes. At the aggregated primary category level patches were divided into one of three categories: 'small', 'medium' and 'larger' patches. Small patches were defined as those with an area greater than or equal to 40,000 m^2 but smaller than or equal to 250,000 m^2. Simple regression was carried out to isolate any significant relationships between percentage change in area of dwarf shrub vegetation in the twenty five smaller patches and each explanatory variable. However, there was no evidence that change was spatially dependent as change was not significantly correlated with a single variable relating to smaller patches. Simple regression was repeated based on the medium-sized patches (area greater than 250,000 m^2 but less than or equal to 2,999,824 m^2). There were thirty eight such patches. Again, no significant relationships resulted. Finally, percentage change in the largest patches was examined (area greater than 2,999,824 m^2). There were twenty eight such patches. Simple regression was repeated but again, no significant relationship resulted. It appeared that percentage change was not dependent on patch size.

Appendix 6

Smoothing Program

This Splus program was used to calculate the density of invasive species which surrounded each pixel. The band width (or kearnal width) could be adjusted to encompass any number of pixesl. In the program below the bandwidth is set to six which is the equivalent of 600 m or three pixels.

```
#You have to set these variables according to the data you are
working with
#Note that you can change the bandwidth
num<-3110
locationx<-idxy78[,1]
locationy<-idxy78[,2]
attribute<-pixinvad78
bandwidth<-seq(1,num)
bandwidth[]<-6.0

#These variables are set up automatically
count<-seq(1,num)
density<-seq(1,num)
distance<-seq(1,num)
length<-seq(1,num)

#set the counter and summation variable to zero
count[]<-0
density[]<-0.0

#Now run the program
#____________________________________________________________
print('Should take about 10 minutes to run')

for(j in 1:num){
   print(j)
   distance<-sqrt(((locationx[]-locationx[j])**2) +
((locationy[]-locationy[j])**2))
   logica<-distance[]<=bandwidth[]
   density[][logica] <- density[][logica] + attribute[j]
   count[][logica] <- count[][logica] + 1
}
#No allowance for zero counts here!
density[]<-density[]/count[]
#____________________________________________________________

test<-cor(pixpchth7887,density)


newsmooth78<-seq(1,pixsum78)
newpixhth78<-seq(1,pixsum78)
```

```
pixsum78<-0
for(i in 1:3110){
if(pixpchth7887[i] <= 0.0){
   pixsum78<-pixsum78+1
   newpixpchth7887[pixsum78]<-pixpchth7887[i]
   newsmooth78[pixsum78]<-density[i]
   newpixhth78[pixsum78]<-pixhth78[i]
 }
}

test<-cor(newpixpchth7887,newsmooth78)

newdata4<- newpixpchth7887[newpixhth78>3000]
newdata5<- newsmooth78[newpixhth78>3000]
cor(newdata4,newdata5)
```

Smoothing Program for the 1987 data

A similar program was used for the 1987 data.

```
#You have to set these variables according to the data you are
working with
#Note that you can change the bandwidth
num<-4751
locationx<-idxy87[,1]
locationy<-idxy87[,2]
attribute<-pixinvad87
bandwidth<-seq(1,num)
bandwidth[]<-8.0

#These variables are set up automatically
count<-seq(1,num)
density<-seq(1,num)
distance<-seq(1,num)
length<-seq(1,num)

#set the counter and summation variable to zero
count[]<-0
density[]<-0.0

#Now run the program
#______________________________________________________________
print('Should take about 10 minutes to run')
for(j in 1:num){
   print(j)
   distance<-sqrt(((locationx[]-locationx[j])**2) +
((locationy[]-locationy[j])**2))
   logica<-distance[]<=bandwidth[]
   density[][logica] <- density[][logica] + attribute[j]
   count[][logica] <- count[][logica] + 1
}
#No allowance for zero counts here!
density[]<-density[]/count[]
#______________________________________________________________
```

```
newsmooth87<-seq(1,pixsum87)
newpixhth87<-seq(1,pixsum87)

pixsum87<-0
for(i in 1:3674){
if(pixpchth8796[i] <= 0.0){
   pixsum87<-pixsum87+1
   newpixpchth8796[pixsum87]<-pixpchth8796[i]
   newsmooth87[pixsum87]<-density[i]
   newpixhth87[pixsum87]<-pixhth87[i]
 }
}

test<-cor(newpixpchth8796,newsmooth87)

newdata4<- newpixpchth8796[newpixhth87>3000]
newdata5<- newsmooth87[newpixhth87>3000]
cor(newdata4,newdata5)

cor(pixinvad87,density)
```

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