Author(s): Sue D M Willis

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THE CLASSIFICATION AND MANAGEMENT OF LIMESTONE PAVEMENTS – AN ENDANGERED HABITAT

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by

SUE WILLIS

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ABSTRACT

This thesis describes an in-depth study of limestone pavements across North West England and North Wales. The aim was to combine elements of geodiversity and biodiversity in order to create a holistic limestone pavement classification to inform future management. A field-based research protocol was used to assess a stratified random sample (46 pavements), accounting for approximately 10% of the limestone pavements in the geographical area. Detailed analyses of key elements are presented, along with important issues that continue to pose threats to this Annex One Priority Habitat.

This research resulted in a comprehensive classification, using TWINSPAN analysis and Nonmetric Multidimensional Scaling, identifying six distinct holistic functional groups. The prime factors driving limestone pavement morphology, and hence the classification, were established to be lithology, proximity to structural fault, altitude and human intervention, particularly in terms of grazing intensity.

Three upland, open limestone pavement classes were formed. Of these, the richest in terms of geodiversity and biodiversity was the group with the thickest bedding planes and hence the deepest grikes, typically greater than 1m. The class that was most species-poor was at the highest altitude (above 450m), formed on the thin limestones of the Yoredales. These were characterised by shallow, wide grikes. The third upland limestone pavement group had mid-range grikes, generally 0.5-1m in depth, and small clints.

Two wooded classes were identified. One was a lowland ‘classic’ wooded limestone pavement group with deep, narrow grikes and shallow soils. Indicator species included Juniperus communis and Taxus baccata. The second wooded group was situated proximal to a major structural fault. In this group the pavement dip ranged between10^{o}-40^{o} with well-runnelled clints that were heavily moss-covered.

The sixth group was low altitude, proximal to the coast, characterised by low moss growth, un-vegetated clints and the presence of Ulex europaeus.

Conservation management was identified as key to the quality of the limestone pavement habitat and this thesis identifies best management practises and links these to the holistic limestone pavement classification.

Finally, as a sample case study, this thesis presents mollusc species and diversity from eleven of the Yorkshire limestone pavements. Analysis establishes significant links between geodiversity and mollusc populations, with key drivers for mollusc communities echoing those of plant species on limestone pavement.

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1 INTRODUCTION AND AIMS

1.1 Introduction to the Thesis

Limestone pavements represent rare and fragile habitats. They are valuable because of their natural beauty, offering a wide range of flora and fauna intertwined with such varied geodiversity. Such is their perceived importance; they are the only natural environments to be protected by criminal law in the United Kingdom and embedded in legislation (Crawford & Burek, In review; Goldie, 1995). Limestone pavements are limited in occurrence throughout Europe and many have been destroyed, disturbed or remain under threat of extraction and vandalism (Pendry & Allen, 1999).

Limestone pavements are defined by Goudie (1990) as “exposed areas of bare limestone both flat and sloping with an array of microforms produced dominantly by solution”, whilst Goldie (1994) refers specifically to the evolutionary history in her definition “limestone outcrops which have been stripped of most or all of any pre-existing soil or other cover by some scouring mechanism, generally but not exclusively glacial scour”.

A compilation of definitions relating to limestone pavement is presented in Table 1-1 and it is notable that they all target the geodiversity of the landform. Geodiversity can be described as “the variety of rocks, fossils, minerals, natural processes, landforms and soils that underlie and determine the character of our landscape and environment” (Stace & Larwood, 2006), and limestone pavement provides a fine example of a habitat containing rich geodiversity. However, current limestone pavement definitions do not refer to their unique and rich biodiversity. Equally, investigations have focussed on single aspects of this habitat and have been heavily weighted towards geodiversity (e.g. Burek & Conway, 2000b; Burek & Legg, 1999b; Goldie & Cox, 2000; Sweeting, 1966; Vincent, 1995).

Table 1-1: Compilation of definitions of limestone pavement

Author	Definition
Jones, R J (1957)	"Essentially…emergent features of the landscape…sculptured by solution while lying beneath the drift and vegetation"
Sweeting, M M (1966)	"Bare rock outcrops occurring in the Karst areas, usually but not essentially, on more or less horizontal beds. Pavements consist of flat-topped rock outcrops known as clints, separated by widened joints or cracks known locally as grykes"
Williams, P W (1966)	"Limestone pavements are glacio-karstic features" "A roughly horizontal exposure of limestone bedrock, the surface of which is either approximately parallel to its bedding or it is divided into a geometrical pattern of blocks by the intersections of widened fissures"
Jennings, J (1971)	"These horizontal or sloping platforms of bare karst are due to exposure of well-bedded, hard limestone to strong Pleistocene glacial erosion"
Sweeting, M M (1972)	"A glaciokarstic landform, produced on a glacially planned limestone surface which has subsequently become dissected into blocks (clints or dalles) by solution-enlargement of vertical joints"
Wildlife and Countryside Act (1981)	"An area of limestone which lies wholly or partly exposed on the surface of the ground and has been fissured by natural erosion"
Trudgill, S (1985b)	"Limestone pavements are areas of bare rock dissected by opened joints and karren forms are sub aerial ones in the shape of pinnacles, small hollows and other morphologies characteristically regarded as being produced by the dissolution of limestones"
Goudie, A (1990)	"Limestone pavements are exposed areas of bare limestone both flat and sloping with an array of microforms produced dominantly by solution"
Goldie, H S (1994)	"Limestone outcrops which have been stripped of most or all of any pre-existing soil or other cover by some scouring mechanism, generally but not exclusively glacial scour"
British Cave Rescue Association (1995)	"A level or gently inclined, bare limestone, surface scored and fretted by karren"
Vincent, P (1995)	"Naked expanses of rock, once scoured by glaciers and now fretted by solution"
Goldie, H S and Cox, N J (2000)	"Limestone pavements are complex assemblages of Karren (or lapiés) landforms generally found on flat-lying or gently dipping strata"
Limestone Pavement Action Group (2003)	"Bare expanses of limestone pavement, criss-crossed by deep fissures, date back to glacial times"

The research that has been conducted on the biodiversity of limestone pavements has equally remained largely uni-disciplinary (Silvertown, 1982; Ward & Evans, 1975), so there remains a dearth of work considering limestone pavements as a holistic habitat, combining both geodiversity and biodiversity. The research presented in this thesis aims to address this omission, combining the diverse aspects of limestone pavement morphology, both geodiversity and biodiversity, in order to produce a holistic classification of limestone pavements.

Limestone pavements are non-renewable habitats on a human timescale as they typically owe their formation to glacial processes. There are many forces at work destroying or irreversibly altering this unique habitat and effective management should be set in place for their continued protection. Such management must be based on a sound scientific footing and it is hoped that this research will influence and direct the long-term management of this fragile habitat.

1.2 Broad Aims of the Thesis

The unique geodiversity and biodiversity of limestone pavements has led to different disciplines researching isolated aspects of the system and consequently there is no recognised overall multidisciplinary classification of limestone pavements. Such a classification is crucial in order to understand their development and achieve well-rounded holistic management of this habitat (Burek & Conway, 2000a; Burek *et al.*, 1998; Conway & Onslow, 1999; Deacon & Burek, 1997).

The broad aim of the project was to produce a functional, holistic classification scheme which could ultimately be used by non discipline specialists worldwide. It aimed to classify limestone pavements according to their geodiversity, biodiversity and overall conservation value. It was then planned to use this classification to examine best practise in management strategies for the different types of pavements and to compile management guidelines related to the classification. It is intended that this will be a valuable tool for informing the management priorities and management plans of conservation agencies.

1.3 Specific Objectives of the Thesis

The specific objectives included:

- Review of current limestone pavement assessment techniques, classifications, management practises and conservation legislation.
- Establishment of a robust, consistent methodology to measure multiple factors during fieldwork.
- Detailed analysis of the geodiversity and biodiversity of a sample of limestone pavements randomly selected from North West England and North Wales.
- Combination of these analyses in order to produce a holistic classification of limestone pavements.
- Linking best practise conservation management objectives to the new holistic classification system.

1.4 Thesis Structure

1.4.1 CHAPTER 1

Chapter 1 introduces the rationale behind the research into the holistic classification of limestone pavement. It defines limestone pavement and details the broad aims and specific objectives of the project. A review of the background literature is included explaining what limestone pavement is, how it evolved, factors that influence the geodiversity and biodiversity of limestone pavement and what the current state of play is regarding the conservation management of this habitat.

1.4.2 CHAPTER 2

Chapter 2 describes the methodology employed in order to carry out a full assessment of the geodiversity and biodiversity of limestone pavements. The rationale for site selection is outlined along with the reasoning behind the approaches and techniques that were adopted. Detailed descriptions of measurement and data recording methods are included in this chapter.

1.4.3 CHAPTER 3

The comprehensive analysis considering the geodiversity of the 46 limestone pavements studied across North West England and North Wales is presented in Chapter 3. Geodiversity results are divided into sections which include geology, landscape scale features, climate, geomorphology and pedology. Key geodiversity results are summarised at the conclusion of this chapter.

1.4.4 CHAPTER 4

Chapter 4 details the analysis of limestone pavement biodiversity variables. Sections include the floral richness of the sites, biodiversity of limestone pavements and grazing regimes, in-depth investigation of the plant communities and discussion regarding limestone pavement fauna. A summary of the biodiversity results are presented at the end of the chapter.

1.4.5 CHAPTER 5

Chapter 5 outlines the development of the holistic classification of limestone pavements from the amalgamation of the geodiversity and biodiversity analyses. Similarities in the plant communities provide the foundation for the functional grouping, which identifies six classes using 43 of the limestone pavements; three limestone pavements proving unclassifiable. The characteristics of each group are identified, including details of the plant indicator species that relate to each group. A flowchart is provided which summarises the key differences between the classifications.

1.4.6 CHAPTER 6

One of the prime aims of the research was to relate the holistic classification to the conservation management of limestone pavement. Chapter 6 provides these links, outlining best practise guidelines for the holistic management of the different classes of limestone pavement. A summary flowchart linking holistic classification with potential management strategies concludes the chapter.

1.4.7 CHAPTER 7

Limestone pavements are rich habitats for fauna and Chapter 7 is a case study, using the holistic classification, focussing on molluscs. The relationship between snails and slugs and different types of limestone pavement environments is examined on eleven of the Yorkshire sites. Mollusc species richness and diversity are analysed and indicator species are identified. Multivariate analysis examines the association between the drivers of plant diversity and those of mollusc diversity and identifies significant similarities. The chapter concludes with a summary of the findings.

1.4.8 CHAPTER 8

Chapter 8 discusses and evaluates the key findings from the thesis and the implications of the research. It highlights aspects of the project that have positively contributed to knowledge of limestone pavement environments and their management. It presents the conclusions of the study and it recognises elements that remain unresolved or require further work.

1.5 Background Literature Review

1.5.1 Introduction to the Literature Review

The aim of this research was to holistically examine limestone pavement in order to produce functional classes for future use in conservation management. It was therefore important to consider all aspects of geodiversity and biodiversity that could indicate distinctions in limestone pavement form. The phrase "geodiversity underpins biodiversity" (Burek, 2001) has gained momentum in recent years but interdisciplinary research to back this assertion is sparse, and evidence lacking (Burek, 1998, 2001; Willis *et al.*, 2007; Willis *et al.*, 2009). This project attempted to investigate limestone pavements across North West England and North Wales with a multidisciplinary approach, examining geodiversity and biodiversity variables and evaluating their interplay.

Literature review examined background information on all aspects of limestone pavements including how they were formed, their distribution, extent, and the major influences on the geodiversity and biodiversity of the habitat. The current position regarding threats to limestone pavement was considered and the literature concerning current classification methods has been summarised and presented.

1.5.2 Limestone Pavement Formation

1.5.2.1 Depositional and Glacial History

Limestone pavement is a type of karst landform. Karst is the word for an area of soluble rock in which the landforms are of a solutional nature (i.e. they are caused by water dissolving the rock) where drainage is usually underground through rock fissures rather than in surface streams. Karst is a term that originates from a limestone region in the former Yugoslavia and is derived from the Slovenian word kras, meaning a bleak, waterless place (Waltham *et al.*, 1997).

The limestone comprising most pavements in the British Isles developed in the Dinantian Stage (Lower Carboniferous or Mississippian) carbonate successions, spanning from 354 to 327 million years ago. This is a period of time when much of Britain and Ireland lay over the equator and developed extensive warm-water, shallow, marine carbonate platforms. During this period there were significant changes in the depositional environment, e.g. the geochemistry and mineralogy, owing to relative changes in sea level which led to a cyclicity in sediment deposition (Vincent, 1995). Ford and Williams (2007) state this is a key determinant of purity, texture, bed thickness and other properties of the limestone.

All areas in Britain and Ireland that possess extensive limestone pavements were glaciated in the Late Devensian i.e. the last glacial period in the British Isles, around 110,000-12,000 years ago, during the latter part of the Pleistocene (Figure 1-1) (Waltham *et al.*, 1997). Absence of limestone pavement in some areas glaciated at this time is likely to be related to the angle of dip, i.e. where limestone beds dip beyond 45° limestone pavement does not develop. Exceptions to this are found at Hutton Roof and Great Asby Scar in South Cumbria (Vincent, 1995).

Figure 1-1: Outline map detailing the main limestone outcrops in Great Britain, reproduced from Waltham, A.C., Simms, M.J., Farrant, A.R., and Goldie, H.S. (1997). The Pleistocene is the epoch from 2,588,000 to 12,000 years BP (Before Present) which covers the most recent period of repeated glaciations, with southern limits of the ice indicated. Palaeozoic limestones are primarily Lower Carboniferous (Devonian limestone in Devon and Cambrian-Ordovician limestone in Scotland). Durness limestone on the Isle of Skye has not been included.

Williams (1966), in Ireland, was the first to publish a summary of limestone pavement formation stating that it begins with glacial erosion which removes superficial material and exposes bedding surfaces. The limestone is then subject to solutional modifications which erases striations and leads to the entrenchment of grikes, runnels and small depressions. This stage, added Williams, is dependent on whether the surface is exposed or covered in glacial till or another substance, with the greatest modification occurring beneath wet vegetation.

Goldie (1976) stated that similar geological structures are found where the action is not a glacial mechanism but wave-cutting at the coast, and on other rocks such as Millstone Grit or Gypsum deposits. Additionally there are areas of limestone where pavements are not found, notably in Derbyshire (Burek, 1978) and the Mendips (Jennings, 1971) and around Cork in Ireland (Mitchell *et al.*, 1973), which Jennings (1971) relates to the fact that these lay outside the limits of the Devensian glaciation.

1.5.2.2 Solutional Weathering

Trudgill (1985a) discusses the processes involved in the solutional weathering (dissolution) of limestone. This takes place when percolating water combines with carbon dioxide in the atmosphere or organic acids (e.g. from decomposition of humus in the soil) to form a weak carbonic acid which reacts with calcium carbonate (the limestone) to produce calcium bicarbonate.

The chemical reactions are as follows:

$CO_2 + H_2O \Rightarrow H_2CO_3$

carbon dioxide + water => carbonic acid

$H_2CO_3 + CaCO_3 \Rightarrow Ca(HCO_3)_2$

carbonic acid + calcium carbonate => calcium bicarbonate (in solution)

By the experimental burying of limestone tablets in a variety of situations Trudgill (1976; 1985a) concluded that weathering rates were greatest under acid soils with drainage, with vegetation type also significantly influencing solution processes. Dunn (2003) concurred; summarising that the rate at which limestone is dissolved under a soil cover depends on soil permeability, as well as temperature, climate, levels of atmospheric carbon dioxide and the levels of organic acids and carbonic acid dissolved in the soil water.

An addition to the above limestone pavement forming processes is the influence of palaeokarstic surfaces i.e. karst features that remain from a previous phase or period of karstification (Somerville *et al.*, 1986; Vanstone, 1998), described in detail by Walkden (1974) and Davies (1991). Vincent

(1995) discussed the presence of palaeokarst with regard to limestone pavement formation, stating that “deep, wide grikes are probably pre-Devensian since they would not have time to form in the post-glacial period”. Such features are evident in modern limestone pavement surfaces as mammilated surfaces or karst pits and add to the complexity of limestone pavement form (Vincent, 2004).

Recent dating studies using Optically Stimulated Luminescence (OSL) techniques by Vincent, Lord, Wilson and Telfer (2009) add to the picture of limestone pavement formation by implicating nivation (processes taking place under a snow cover). Meltwater from snow patches lying on limestone pavement areas during periods of colder climate are believed to have increased denudation and accordant geomorphic activity (Vincent *et al.*, 2009).

1.5.3 Distribution and Extent of Limestone Pavement Habitats

Limestone pavement is a globally rare landform found primarily in Britain and especially in Ireland. The prime location is in the Republic of Ireland in the Clare-Galway area (termed the ‘Burren’) and on the Aran Isles in Western Ireland, with a total estimate of 31,100 ha (Murphy & Fernandez, 2009). Limestone pavement is also found in Fermanagh in Northern Ireland (Burek & Conway, 2000a).

Waltham, Simms, Farrant and Goldie (1997) argued that “the Yorkshire Dales contain Britain’s finest glaciokarst” with the largest distribution on the Carboniferous Great Scar Limestone in the southern Pennines, around Ingleborough and Malham. Other areas in England where limestone pavements can be found include Cumbria, notably Great Asby Scar, and around Morecambe Bay which includes important limestone pavements such as the Grange pavements, Hutton Roof, Farleton Knott and Gait Barrows. There are smaller limestone pavement outcrops found in North and South Wales and in the Forest of Dean (see Figure 1-2).

The above limestone pavements lie on Carboniferous limestones, but in Scotland there are small limestone pavement outcrops on older limestones including Dalradian limestone in Perthshire, Cambrian limestone on Skye and in the Durness area of Sutherland (Goldie & Cox, 2000). These are considered particularly valuable because they "represent an extremely unusual geological and floristic variant" (JNCC, 2007).

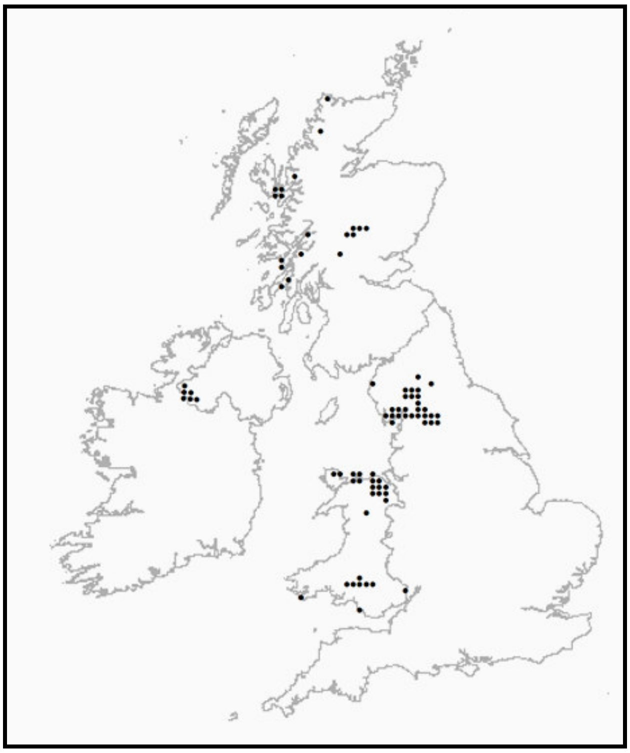

Figure 1-2 UK distribution of limestone pavement, estimated to total 2,818 ha (map courtesy JNCC, 2007).

Further afield within Europe a small distribution of limestone pavement is found in Öland, Sweden, and in Sardinia (Webb & Glading, 1998); with fragmentary occurrences in the high Alps (JNCC, 2007). In the USA/Canada, limestone pavement is located in the Great Lakes region including Chaumont Barrens (Feeney, 1996) and Syracuse in New York State (Burek & Conway, 2000a); and Bruce Peninsula in Canada (Lundholm & Larson, 2003).

1.5.4 Factors Influencing Limestone Pavement Geodiversity

1.5.4.1 Stratigraphy and Lithology

Williams (1966) stated that "the most basic feature of any pavement is the stratum on which it developed…and so a classification should acknowledge this fact". The outline classification he devised considered the attitude of the limestone pavement beds, but he summarised that each limestone pavement is unique in morphology with the patterns of grikes and runnels and the extent of their enlargement being key.

Sweeting postulated that lithological variations are probably the most important cause of contrast between one pavement and another, classifying pavements into thinly-bedded types and massively-bedded types. Generally, she stated, thinly-bedded limestone pavements tend to be strongly affected by mechanical weathering, particularly by frost action, and weakly by solutional weathering with the reverse true of the more massive sections. On thinly-bedded limestones the grikes tend to be shallow (usually less than one metre deep), narrow (half a metre wide), and are frequently overgrown with vegetation. The clints weather mostly along planes of bedding. In contrast, on massively-bedded limestones, the solution takes place along vertical lines of jointing. The limestone pavements are cut by deep grikes, frequently over two metres, with beds consisting of hard-blue impermeable limestone which is resistant to frost weathering (Sweeting, 1966).

1.5.4.2 Structure

In 1972, Sweeting stated that the degree of jointing was one of the most important factors affecting the morphology of limestone pavements, citing the work of Wager (1931), who noticed that in Yorkshire the clints are generally rectangular or parallelogram-shaped because of the occurrence of two sets of master joints. Typically clints are one metre by two metres with frequency of jointing increasing near fault lines, resulting in knife-like clints 300-500mm wide (Sweeting, 1972).

Goldie (1976) examined thin sections of pavement limestone from Yorkshire, Cumbria and Switzerland for texture, structure, sparry calcite content, fossil content and associated minerals such as iron, quartz, gypsum and dolomite. She was unable to demonstrate a conclusive relationship between sparry calcite content and runnel, grike or clint width or depth. Goldie's conclusion was that despite considerable variation in lithology of pavements in the areas she studied some of the pavement morphometric features were surprisingly similar. Goldie was able to establish that coarser limestones form significantly larger clints than those formed on the finer limestones (Goldie, 1976).

1.5.4.3 Soils and Geomorphology

Zseni, Goldie and Bárány-Kevei (2003) researched the connection between the solutional power of soil and the geomorphology of limestone pavements, in particular the depth, smoothness and roundness of the limestone. The authors investigated the pH and carbonate content of soil samples from runnels, grikes, foot of pavements and clints on limestone pavement areas in the north of England. They found that soils with lower pH were related to deeper solution features, concluding that acid soils increase solutional weathering. They also found that the limestone had an effect on the soil as soils proximal to limestone had a significantly higher pH (Zseni *et al.*, 2003).

1.5.5 Factors Influencing Limestone Pavement Biodiversity

1.5.5.1 Soils and Biodiversity

It is widely recognised that bare limestone pavements in Britain were once covered in soil (Jones, 1965; Sweeting, 1966; Trudgill, 1976), which is evidenced by the presence of runnels (rundkarren) on most limestone pavements, formed by subsoil weathering, as discussed in Section 1.5.4.3. Forestation of the British Isles is estimated to have been complete by 8 ka across all but the very highest and most exposed parts of the country (Chapman, 2007), which pollen studies have confirmed (e.g. Gosden, 1968). Deforestation by man began in the Neolithic (5.5 ka) and radically altered the landscape in karst regions (Drew, 1983; Goudie & Brunsden, 1994; Raistrick, 1983; Ratcliffe, 1984), destabilising soils and vegetation. Added to this has been the overuse of limestone areas for grazing stock, especially sheep, which has contributed to degradation of limestone pavement habitats (e.g. JNCC, 2007).

Soils appreciably influence limestone pavement biodiversity and there are several distinct soils associated with limestone pavements (Burek *et al.*, 1998; Carroll, 1986; Conway, 2007). Carboniferous limestone comprises very pure calcium carbonate ($CaCO_3$) with little insoluble residue (less than five per cent). Consequently soils derived from weathering of the limestone tend to be shallow and calcareous, termed rendzina soils. Soil pH has an important relationship with plant community structure (Ellenberg, 1988; Moles *et al.*, 2003) and calcareous substrates are particularly limited in occurrence in Britain; thus they are protected as Biodiversity Action Plan (BAP) habitats (JNCC, 2007).

Other soils associated with limestone pavements result from glacial deposition in the form of glacial till. This comprises unsorted glacial sediment ranging in size from boulders to clay (Burek & Cubitt, 1991; Clayton, 1981). Glacial till can vary in depth, organic matter content, colour, particle-size, acidity, clay content, geochemistry and moisture levels. Till is often quite local in origin and tends to reflect the local geology (Carroll, 1986), but the geochemistry, especially trace element analysis, can indicate its far-travelled nature (Burek & Cubitt, 1991). Thom, Swain, Brandes, Burrows, Gill and Tupholme (2003) suggest that the amount of till remaining on the surface of the clints (such as at Scar Close) may explain the variance in plant diversity between limestone pavements in the Yorkshire Dales National Park.

Superficial to the glacial till, or incorporated into it, there may be silt-sized wind-blown material called loess, almost always comprising the mineral quartz (SiO_2). The loess deposits on the Morecambe Bay limestone pavements are described by Vincent and Lee (1981) as widespread and relatively thick (0.3m), although thicknesses of up to 1.5m have been recorded in places across Northern England (Vincent *et al.*, 2009). Vincent and Lee noted a strong spatial correlation between the presence of *Calluna vulgaris* (Heather) and *Pteridium aquilinum* (Bracken) and areas of loess sediments. Both of these plant species are calcifuges i.e. plants intolerant of base-rich soils, and Vincent and Lee suggest that the acidic loess provides a "lime-free buffer zone" between the plant and the underlying limestone (Vincent & Lee, 1981). This relationship between soil pH and biodiversity on limestone pavement is also discussed by Gray (2004) contributing to his conjecture that "geodiversity underpins biodiversity", a phrase developed by Burek (2001).

1.5.5.2 Environmental Heterogeneity and Microclimate

Several investigations have been conducted that study the relationships between the limestone pavement structural environment and their plant communities. Limestone pavements are noted for environmental heterogeneity and unique microclimates within the grikes (Burek & Legg, 1999b; Burek & York, 2009; Yarranton & Beasleigh, 1968, 1969). Lundholm and Larson (2003) found that higher species richness on limestone pavement alvar in Ontario, Canada was associated with greater spatial heterogeneity in microsite composition and soil depth. Silvertown (1982) describes grikes as niche spaces and states that they have a microclimate of their own with specific plants having their own preferences. Yarranton (1970) found that bryophyte and lichen species correlate closely at the base of grikes, which Silvertown's work supported, concluding that competition between species seemed to play no significant role in the distribution of grike vegetation on limestone pavement (Silvertown, 1983).

Alexander, Burek and Gibbs (2005) investigated the effect of grike orientation on microclimate, collecting data over the course of 46 weeks from grikes on a Cumbrian limestone pavement. They found north-south orientated grikes were better lit, warmer, less humid, with a greater range of temperatures and photosynthetically active radiation (PAR). East-west grikes were darker, cooler, more humid, and had more frost events. Temperature was also found to vary with ranges at a maximum at the surface, attenuating with depth. Notable was the reduction in temperature range below 0.70m depth, with stability of temperature and lack of frost at the base of the grikes (Alexander *et al.*, 2005). These findings concurred with Heslop-Harrison (1960), Yarranton and Beasleigh (1969) and Burek and Legg (1999b); all of whom demonstrated a marked stratification in grike temperature with depth. They noted lower more stable temperatures at the grike base, fluctuating nearer the surface and the narrower the grike the more pronounced the variance.

Plant surveys on limestone pavements in Wales have shown an increase in abundance and diversity in north-south orientated grikes (Inman, 2000; Lloyd-Jones, 2001). This was also found to be the case with mollusc studies on limestone pavements in Wales, with greater numbers of snails found in north-south grikes at Bryn Alyn and Y Taranau (Lloyd-Jones, 2001; Swindail, 2005).

1.5.5.3 Other Influential Factors in Limestone Pavement Biodiversity

Osborne, Black, Lanigan, Perks and Clabby (2003) considered the factors influencing growth patterns of three plant species in grikes on the Burren, Co. Clare. Here rainfall is high, averaging 1200-1700mm per annum, yet the authors concluded that water availability could be growth-limiting due to the limestone substrate. Limestone has a very low water-holding capacity with over 60% of rainfall running straight off (Drew, 1990) and limestone pavement soils often have limited organic matter, so water retention capacity is poor (Osborne *et al.*, 2003). All three plant species examined demonstrated evidence of water deficiency which limited the plants ability to photosynthesise. Similar results were obtained by Schaefer and Larson (1997) in their investigation of seven alvar sites in Canada. Alvars are similar to limestone pavements with thin soils over essentially flat limestone or marble rock and a sparse vegetation cover of shrubs and herbs, with trees absent or at least not forming a continuous canopy (Catling & Brownell, 1995). Schaefer and Larson hypothesised that drought may be the factor defining vegetation suppression in shallow soiled alvars (Schaefer & Larson, 1997).

Figure 1-3: *Nostoc*, a genus of cyanobacteria (blue-green algae), colonising a solution pan on Dale Head limestone pavement, Pen-y-Ghent.

The impermeability of the limestone strata is also an important feature in the development of the micro-geomorphology of the clints on limestone pavement. Solution pans (also termed kamenitzas, solution cups or solution hollows) form on reasonably horizontal limestone pavement when rainwater lodges in miniature topographic depressions leading to *in situ* solution (Lowe, 1981; Sweeting, 1966). Biotic factors then play a significant part in deepening and widening the solution pans, initially by colonisation by algae (Figure 1-3), followed by accumulations of mosses (especially *Fissidens* spp.) and lichens, when conditions are suitable (Ivimey-Cook, 1965; Lowe, 1981).

1.5.6 Threats to the Habitat

Following an extensive survey of British limestone pavements for the Institute of Terrestrial Ecology in the early 1970s, Ward and Evans (1976) declared that, of the estimated 2,600 hectares in Britain, over 40% of the habitat had been completely destroyed. They estimated that most pavements were damaged to a greater or lesser degree, with only 3% entirely intact. These results were persuasive in securing greater statutory protection through the passing of the 1981 Wildlife and Countryside Act, Section 34, which contains a provision for making Limestone Pavement Orders (LPOs) by local authorities (HMSO, 1981). Additionally, in 1992, the European Parliament asked Britain to safeguard this fragile landscape under European Habitats Directive EEC 92/43, which lists limestone pavements as an Annex I Priority Habitat (McLeod *et al.*, 2005).

In 2004 the Limestone Pavement Action Group (LPAG) outlined the following as key threats to the habitat:

- Inappropriate levels of grazing.
- In-filling of grikes (to prevent livestock from becoming stuck in the grikes).
- Cessation of management on wooded limestone pavement.
- Illegal removal of pavement.
- Demand from the public for 'water-worn limestone', unaware of its ecological importance.

Human interference with limestone pavement has been well documented by Goldie (1976; 1986; 1993) with major factors including quarrying and damage to the limestone around mineral workings and lime kilns. Sweeting (1966) mentioned the "firms" who had been exploiting surface layers of pavement for many years, stating that farmers encouraged this exploitation as it extended their grazing areas.

Protection measures came into force in the 1990s when LPOs were granted on most of the major limestone pavement areas in England. The current state of play is summarised by Crawford and Burek (In review) who conclude that overall protection measures are largely working in Britain, whilst extraction and destruction of limestone pavement continues in the Republic of Ireland (Pendry & Allen, 1999). Demand for water-worn rockery stone for gardens continues to fuel the trade, as identified in the TRAFFIC International report "On Stony Ground" (Pendry & Allen, 1999), and limestone pavement remains an endangered finite habitat.

Van Beynen and Townsend (2005) considered all the factors which 'disturb' karst environments. They devised an index which denotes the degree of disturbance to the karst area on a five-point numerical scale between 'pristine' and ‘highly disturbed’. Categories of disturbance are broad and include geomorphology, atmosphere, hydrology, biota and culture, covering both macro and micro scales. Van Beynen and Townsend take a holistic view on the threats to karst and state that human pressure on these environments is increasing worldwide. The index could be used to quantify the current disturbance to limestone pavement and make comparisons between the threats to the habitat in different geographical areas such as Britain and the Republic of Ireland.

1.5.7 Current Classification of Limestone Pavement

Several authors have considered ways to classify limestone pavement over the years and an outline of the key points of each classification generated is presented in Table 1-2, ordered by publication date. Generally classification considers aspects of geodiversity or biodiversity independently but more recent work by Ellis (2007) and Murphy and Fernandez (2009) has begun to combine these elements and regard the habitat holistically. Indications are given in Table 1-2 regarding the nature of the classification described i.e. geodiversity (GEO), biodiversity (BIO) and holistic (HOL).

1.5.8 Summary of Literature Review

A summary of the relevant literature relating to limestone pavement habitats is presented in this review, particularly focussing on research that links the geodiversity of the limestone pavement with the biodiversity. Current thinking on limestone pavement classification is also summarised. Specific research literature relating to aspects of the methodology, geodiversity, biodiversity and management practises is also incorporated into the relevant chapters in the thesis.

The literature review informed the methodology that was used to differentiate and classify the limestone pavements examined in this study. Variables investigated were from those facets of limestone pavement geodiversity and biodiversity that research has shown to influence limestone pavement form and are summarised in this chapter.

Table 1-2: Review of existing limestone pavement classifications with type identified (GEO=geodiversity, BIO=biodiversity and HOL=Holistic)

Author(s) and Date	Area Studied	Variables Considered	Classification Details	Type
Sweeting, M (1966)	N. England	Lithology	Sweeting defined 2 limestone pavement types from her extensive observations, based on the thickness of bedding planes: thinly-bedded and massively-bedded.	GEO
Williams, P W (1966)	UK and Republic of Ireland	Attitude of pavement beds	Williams produced 3 classes of limestone pavement based on the attitude of the limestone beds: 'horizontal', 'inclined' and 'arched'. He added that 'stepped pavement' on hillsides (schichttreppenkarst) should also be acknowledged.	GEO
Ward and Evans (1975)	British pavements	Botanical quality	Ward and Evans did extensive fieldwork across Britain. They devised a floristic index based on the conservation value of limestone pavement plant species. Pavement was categorised into 3 groups: >91 (highest botanical quality); 71-90 (lower botanical quality); <71 (lowest botanical quality).	BIO
Waltham and Tillotson (1989)	Ingleborough, N. Yorkshire	Geomorphology	This classification of the geomorphology of Ingleborough pavements took into account certain pavement features or types including rillenkarren; deep grikes; flaggy; kamenitzas; linear; massive; normal (unremarkable pavement – not 'quality'); rundkarren; wide grikes; gently dipping; steeply dipping, along with a qualitative assessment of overall morphology.	GEO
Catling and Brownell, (1995)	US/Canada	Flora on alvars, US/Canadian pavements	120 alvars were assessed and 2 major classes were formed on the basis of floral composition and environmental factors (primarily soil depth, slope and moisture). Classification was 'shoreline alvars along rivers and lakes' and 'plateau alvars'. 4 floral sub-communities were identified on plateau alvars.	BIO
Deacon and Burek (1997)	Wales	Botanical and geomorphological features	38 limestone pavements in Wales were visited. Five categories were outlined: Upland grazed/Wooded/Thinly bedded/Massively bedded/Coastal (tidal zone). Pavements studied were not assigned to these categories however.	HOL
Waltham *et al*., (1997)	British karst, UK wide	Overall quality of the karst landforms for designation as SSSIs	A survey of the geomorphology of karst surface landforms was undertaken and, in liaison with specialists countrywide, a new set of geological SSSIs was established, based on quality-based criteria.	GEO
Burek, C V (1998)	Little Orme and Bryn Pydew, N. Wales	Vegetation, clints and solution features	Description of 2 limestone pavements using ternary diagrams to describe composition of the pavement in terms of overall percentage of vegetation cover, clint area and solution features.	HOL
Webb and Glading (1998)	British pavements	Ecology	Two general classes of limestone pavement are presented in this paper: 'open' and 'wooded'.	BIO
Coward, S (2002)	Bryn Pydew and Bryn Alyn, N. Wales	Vegetation, clints and solution features and seasonal variations.	Description of 2 limestone pavements using ternary diagrams to outline the composition of the pavement in terms of overall percentage of vegetation cover, clint area and solution features. Winter and summer variations are also presented.	HOL
Thom *et al.* (2003)	Yorkshire Dales National Park, England	Botanical quality	This report re-surveyed Ward and Evans (1975) limestone pavement stands, comparing biodiversity values using their Floristic Index (FI). 211 of 235 pavements were surveyed. Results were a 33% decrease in high quality pavements and the condition of 92% was assessed to be 'Unfavourable' with 28% declining in quality. The area of pavement; amount of damage and percentage of scrub cover explained only 51% of the variation in the FI with the remainder unexplained by those variables analysed.	BIO

Author(s) and Date	Area Studied	Variables Considered	Classification Details	Type
Huxter, E A (2004)	Newbiggin Crags and Hutton Roof, Lancs.	Abiotic classes and lichen distribution using remote sensing.	Huxter used remote sensing to describe two limestone pavements. Abiotic classes formed were 'massive', 'flaggy' and 'pseudobrecciate' limestone pavement with 'shillow' and 'damaged pavement' classes. Lichen distribution was also examined using remote sensing techniques. Huxter identified limitations in the use of remote sensing techniques and stated that as yet there was no ideal sensor available.	GEO
Leach, H (2004)	Ystradfellte, S. Wales and Great Orme, N. Wales	Vegetation, clints and solution features and seasonal variations.	Description of two limestone pavements using ternary diagrams to outline the composition of the pavement in terms of overall percentage of vegetation cover, clint area and solution features. Winter and summer variations are also presented.	HOL
Vincent, P (2004)	Northern England	Polygenetic origin	Vincent suggests that there are genetically four types of pavement in northern England namely: glacially eroded joint-dominant pavements; glacially exhumed calcrete-dominant pavements without palaeokarst; glacially exhumed calcrete-dominant pavements with palaeokarst; glacially truncated palaeokarst.	GEO
Van Beynen and Townsend (2005)	General Karst, Worldwide	Disturbance factors	Van Beynen and Townsend classified all the factors which 'disturb' karst environments (including limestone pavements), coming up with a numerical scale which classifies the karst area by its level of disturbance. This includes human, environmental and biological factors. This was done to aid priority setting for conservationists.	HOL
Parr *et al.* (2006)	Burren, Republic of Ireland	Broad habitat type	Satellite imagery (Landsat) was used to survey and map the extent and spatial distribution of broad habitat types within the Burren. A digitised habitat map was produced which will be used to monitor vegetation change in the Burren. Images were ground-truthed by fieldwork data. 15 habitat types were identified with 2 limestone pavement classes: 'vegetated' and 'bare', comprising 20% of the habitat.	BIO
Ellis, G (2007)	Brecon Beacons National Park, Wales	Geodiversity	Ellis mapped and surveyed limestone pavements in the Brecon Beacons National Park using a new tool he devised called the Pavement Formation Assessment (PFA). Grades were allocated based on the 'extent of exposure' (continuous, scattered or fragmented) and the 'condition of exposure' (intact, damaged, broken, collapsed or destroyed). These were detailed for each pavement and added to a biological condition assessment.	GEO
Murphy and Fernandez (2009)	Ireland	Limestone pavement habitat types	Murphy and Fernandez classified Irish limestone pavements and associated habitats based on vegetation and morphology. Four main habitat types were defined: limestone pavement, heath, grassland, and scrub with limestone pavement sub-divided into 'shattered' and 'blocky'. Detailed recording of higher and lower plants was made along with an outline summary of the geodiversity data. Plant indicator species associated with each group were deduced.	BIO
Joint Nature Conservation Committee (2010)	British pavements	Grading of UK SACs based on 'feature interest'	Interest rating given to SACs where: Grade A=Outstanding examples of the feature in a European context. Grade B=Excellent examples of the feature, significantly above the threshold for SSSI/ASSI notification. Grade C=Examples of the feature which are of at least national importance. Grade D=Features of below SSSI quality occurring on SACs.	BIO

2 METHODOLOGY

2.1 Introduction

The purpose of this study was to examine holistically the critical differences in limestone pavement areas across North West Britain, both in their geodiversity and their biodiversity. Having established these differences the aim was then to classify limestone pavements into functional groups in order to aid the understanding, conservation and management of these rare habitats.

The development of the methodology for the holistic assessment of limestone pavements has therefore involved taking a broad perspective whilst reviewing the literature and assessing the utility of previous approaches to a holistic study. The resultant field-based research protocol presented in this chapter satisfies the aims of the study and offers a unique contribution to the holistic assessment of limestone pavement for multidisciplinary use.

Although existing information was examined closely, previous studies have largely been conducted in a uni-disciplinary manner, examining individually the geodiversity, biodiversity or the microclimatology of limestone pavements (Burek & Legg, 1999b; Goldie, 1976; Goldie & Cox, 2000; Silvertown, 1983; Ward & Evans, 1975; Yarranton, 1970).

Additionally, recent works on digitally mapping limestone pavement areas in England and Ireland were examined. These studies used remote sensing techniques to assess large-scale pavement areas; an invaluable tool for obtaining both the extent of the more open pavement areas and the main vegetation types present (Huxter, 2004; Parr *et al.*, 2006). However this approach lacks the ability to collate the micro-environmental and plant data thought essential to meet the aims of this research. It also has limited value when assessing wooded limestone pavement areas due to the canopy cover. For these reasons a field-based approach was adopted.

Pilot studies at the University of Chester had suggested that a significant contribution to the holistic classification of limestone pavement may be offered by assessing and comparing the vegetation and karst features on pavements using ternary diagrams (Burek, 1998; Coward, 2002; Leach, 2004). Ternary diagrams are triangular graphs that allow three axes to be represented together for comparison. This concept has been explored further within this study in Chapter 5, Section 5-6.

The approach in this research has, therefore, been to devise a new and rigorous field-based research methodology incorporating the examination of all the key elements of biodiversity, geodiversity and micro-environmental conditions on limestone pavements. This methodology has included the use of standardised, well-established techniques as far as possible to ensure that the data collected are robust.

Fieldwork was carried out from April to late September of 2007 and 2008 in order to work during the growing season and thereby enable identification of the maximum number of plant species. This was consistent with guidelines on monitoring limestone pavements (JNCC, 1997). Wooded pavements were visited early in the field season to enable the geomorphology to be assessed before it was masked by plant growth. Full details of the timings of fieldwork and species recorded can be found in Appendices A, B and C.

2.2 Scope of Study and Inclusion Criteria

2.2.1 <u>Habitat Definition</u>

The Wildlife and Countryside Act (HMSO, 1981, amended 1985) defines limestone pavement as "an area of limestone which lies wholly or partly exposed on the surface of the ground and has been fissured by natural erosion". This forms the basis of the habitat definition used in this study along with the clarification developed by Natural England (Webb, 7th March 2007, pers. comm.), namely "that it demonstrates a pattern of clints and grikes".

However, for the purposes of precision, particularly when digitally mapping limestone pavement areas, the UK-Ireland Limestone Pavement Group has developed this definition further (Appendix D). In 2007 they wrote:

"Mapping of limestone pavement requires some form of remote sensing, typically aerial photographs or satellite imagery, upon which potential mapping units can be delimited. Within that context, it is suggested that:

- *where exposed limestone within a boundary delimited by the interpreter on aerial photographs equals or exceeds 75% by area, this constitutes limestone pavement proper. This may be regarded as 'classic pavement'.*
- *where a pattern of clints and grikes can be discerned, but is overlain by vegetation comprising 25% or more of the area delimited by the interpreter, this constitutes a mosaic with grassland, heath, woodland, saltmarsh, etc. These are the more fragmentary limestone pavements within a matrix of grassland, heath, scrub, woodland or other habitats.*

It is suggested that both are mapped as UKBAP Habitat Limestone Pavement for the purposes of this exercise; at a future date polygons of areas of 'classic pavement' can be delimited" (Ward, 2007).

From a holistic viewpoint, it has become evident to the author during this research that defining the extent of the limestone pavement area can vary, dependent on the discipline of the observer, particularly when the clint and grike structure is evident but masked by vegetation. In this example, geologists may use the term 'evolving pavement area' where an ecologist may consider that this is not pavement at all, rather an alternative habitat such as limestone grassland, heath or saltmarsh depending on the floral community present. In the author's opinion the definition of limestone pavement would benefit from further refinement to ensure that there is a holistic definition encompassing the perspectives of all disciplines. A new definition by the author is:

"A partially or wholly exposed area of limestone, fissured by natural erosion into a pattern of clints and grikes, with a distinctive and unique plant community which characterises the microclimates of the grikes."

It is proposed that this could be used with the habitat definition (Ward, 2007, Appendix D) to ensure the holistic character of limestone pavement is clear.

2.2.2 Inclusion Criteria

All limestone pavements that met criteria in 2.2.1 were included except for the following:

- Outcrops where the pavement area meeting the above definition was of insufficient size to carry out a full assessment, specifically those sites offering less than five distinct and measurable grikes/clints.
- Areas of maritime, lacustrine or riverine limestone platforms that have solely been created by water-flow and/or wave action.
- ‘Rocks in grass’ areas where the bedrock is so masked by vegetation, such as grassland, that clint and grike patterns are indistinct and therefore un-measurable.

2.3 Site Selection

2.3.1 Rationale for Pavement Selection

The rationale for site selection was to assess as large and representative a sample of limestone pavement habitats as feasible within the logistical constraints of the study. In the early 1970s, Ward and Evans undertook a landmark study of limestone pavement in Great Britain (Ward & Evans, 1975). Pavements in their study were primarily grouped according to geography; though even at this time the shallow-bedded pavements in the Yoredale Group were set apart on the basis of their lithology. This comprehensive work was subsequently used in the JNCC guidelines for the selection of National Nature Reserves (NNRs) and Sites of Special Scientific Interest (SSSIs) (JNCC, 1989) whilst strongly influencing the subsequent placement of LPOs and their inclusion in subsequent legislation (HMSO, 1981; Webb & Glading, 1998).

Ward and Evans created nine groupings of pavements in total, of which there are five across Northern England and North Wales, namely the North Wales pavements; Morecambe Bay pavements; Hutton Roof pavements; North Yorkshire pavements; North Yorkshire pavements (Yoredale series) and North Cumbrian pavements. Further to this, Ward and Evans assessed individual pavement stands in discrete units, which were approximately of a similar size.

Following literature search and extensive discussions with both Natural England (NE) and the Countryside Council for Wales (CCW) it was decided, for the purposes of this study, to base a stratified random sample of limestone pavements on these five Ward and Evans groupings. Stratification of the groups ensured that a representative sample of pavements was obtained across the geographical area. A further benefit of using sites that had previously been surveyed meant that comparative analysis of the pavement stands over time would be possible, a valuable addition to the research findings.

It was noted, however, that this previous work had largely excluded wooded limestone pavements. In Wales an initial study to assess and locate limestone pavements across the Principality was sponsored by CCW in 1996. This looked at pavements, including wooded pavements, not identified from aerial photography by Ward and Evans. This work was undertaken by Deacon as an MSc project and published as a CCW contract report (Deacon & Burek, 1997) continuing under the auspices of the Regionally Important Geodiversity Sites (RIGS) groups in Wales (Burek, 2008).

Table 2-1: Summary of the location of the 565 limestone pavements (LPs) in the study area. The pavements to be studied were selected from within these groupings using a random number generator (Urbaniak & Plous, 2007).

Location	Ward and Evans (1975) pavement stands	Additional LPs from NEWRIGS, G&M RIGS, CCW, NE, YDNPA	Totals
Cumbria	89 pavements	1 wooded	90
Hutton Roof	56 pavements	3 wooded	59
Morecambe Bay	134 pavements	16 wooded	150
North Wales - Anglesey	1 pavement	13	14
North Wales - Other	11 pavements	19	30
Yorks - Ingleborough	77 pavements	1 wooded	78
Yorks - Kingsdale/Whernside/ Pen-y-Ghent	58 pavements	-	58
Yorks - Malham/Arncliffe/Conistone	78 pavements	2 wooded	80
Yorks - Yoredales	6 pavements	-	6

Thus, to ensure that a representative selection of all pavement types was made, additional wooded pavements, identified since Ward and Evans' work, were added to the stratified groupings, along with 32 additional small Welsh pavements. Details of these additional pavements were obtained from the databases of the North East Wales (NEWRIGS) and Gwynedd and Môn

(G&M) RIGS Groups, Countryside Council for Wales (CCW), Natural England (NE) and the Yorkshire Dales National Park Authority (YDNPA). In total, 565 pavement units were identified within the study area (see Table 2-1).

2.3.2 Selected Sites

Final pavement stand selection, based on the stratified random sampling, is presented in Table 2-2. Small variations in the definitive selection of the pavements occurred due to problems with permission for access or when pavement stands that had been randomly selected were unsuitable for assessment due to their very small size (see Section 2.2.2) or due to extensive damage at the site. Where this occurred the geographically closest and assessable pavement stand was substituted.

Table 2-2: The stratified random sample of limestone pavements assessed during this study.

Pavement Group	Ward and Evans unit	Study Code	Pavement name	Grid ref
Cumbria (CU)	The Clouds stand 5	CUCLO	Fell End Clouds	SD737998
Cumbria (CU)	Gt Asby stand 44	CUGAS	Great Asby Scar	NY657104
Cumbria (CU)	Gt Asby stand 24	CURA	Royalty Allotment	NY645105
Cumbria (CU)	Gt Asby stand 19	CUSB	Sayle Bottom	NY655110
Cumbria (CU)	Gt Asby stand 58	CUSUN	Sunbiggin	NY646090
Hutton Roof (HR)	Hutton Roof Complex stand 48A	HRCRAG	Hutton Roof Crags	SD557776
Hutton Roof (HR)	Hutton Roof Complex stand 36	HRDAL	Dalton Crags	SD552770
Hutton Roof (HR)	Hutton Roof Complex stand 13	HRHPE	Holme Park Fell East	SD547790
Hutton Roof (HR)	Hutton Roof Complex stand 7	HRHPW	Holme Park West	SD540796
Hutton Roof (HR)	Hutton Roof Complex stand 20	HRHQ	Holme Park Quarry	SD538788
Morecambe Bay (MB)	Whitbarrow stands 34/35	MBFAR	Farrar's Allotment	SD451860
Morecambe Bay (MB)	Morecambe Bay East stand 17	MBGB	Gait Barrows	SD479772
Morecambe Bay (MB)	Hampsfield Fell stand 22	MBHFA	High Farm Allotment	SD404791
Morecambe Bay (MB)	No	MBHW	Hampsfield Wood	SD402805
Morecambe Bay (MB)	No	MBTQ	Trowbarrow Quarry	SD481761
Morecambe Bay (MB)	No	MBUW	Underlaid Wood	SD485790
North Wales (NW)	North Wales stand 21	NWBA	Bryn Alyn	SJ198589
North Wales - Anglesey (NW)	No	NWBON	Boncs (aka Pentre Carreg Bach)	SH504839
North Wales (NW)	North Wales stand 16	NWBP	Bryn Pydew (aka Pen y Bont)	SH817798
North Wales (NW)	North Wales stand 14	NWGO	Great Orme	SH757839
North Wales - Anglesey (NW)	No	NWMOE	Moelfre	SH514868
North Wales (NW)	No	NWTAR	Taranau	SJ182720
Yorks - Ingleborough (IB)	Ingleborough stand 73	IBCLAP	Clapdale Scars	SD749709

Pavement Group (cont.)	Ward and Evans unit	Study Code	Pavement name	Grid ref
Yorks - Ingleborough (IB)	Ingleborough stand 36	IBCOLT	Colt Park Wood	SD774778
Yorks - Ingleborough (IB)	Ingleborough stand 63	IBCRUM	Crummack Dale	SD772719
Yorks - Ingleborough (IB)	Ingleborough stand 29	IBSCAR	Scar Close	SD748771
Yorks - Ingleborough (IB)	Ingleborough stand 44	IBSUL	Sulber	SD774738
Yorks - Ingleborough (IB)	Ingleborough stand 41	IBTC	Top Cow	SD782759
Yorks - Kingsdale/ Whernside/ Pen-y-Ghent (KWP)	Pen-y-Ghent stand 8	KWPDH	Dale Head	SD840714
Yorks - Kingsdale/ Whernside/ Pen-y-Ghent (KWP)	Whernside stand 6	KWPEWE	Ewe's Top	SD704758
Yorks - Kingsdale/ Whernside/ Pen-y-Ghent (KWP)	Feizor stand 21	KWPLS	Little Stainforth	SD810662
Yorks - Kingsdale/ Whernside/ Pen-y-Ghent (KWP)	Pen-y-Ghent stand 1	KWPOLD	Old Ing	SD782774
Yorks - Kingsdale/ Whernside/ Pen-y-Ghent (KWP)	Feizor stand 1	KWPOX	Oxenber Wood	SD781683
Yorks - Kingsdale/ Whernside/ Pen-y-Ghent (KWP)	Feizor stand 5	KWPSC	Smearsett Copys	SD799683
Yorks - Malham/ Arncliffe/ Conistone (MAC)	Malham-Arncliffe stand 34	MACBOR	Bordley	SD954648
Yorks - Malham/ Arncliffe/ Conistone (MAC)	Conistone stands 25a/25b	MACBW	Bastow Wood	SD994654
Yorks - Malham/ Arncliffe/ Conistone (MAC)	Conistone stand 9	MACHCS	Hill Castles Scar	SD991684
Yorks - Malham/ Arncliffe/ Conistone (MAC)	Conistone stand OA	MACLAN	Langcliffe	SD983721
Yorks - Malham/ Arncliffe/ Conistone (MAC)	Conistone stand 21	MACLG	Lea Green	SD997662
Yorks - Malham/ Arncliffe/ Conistone (MAC)	Malham-Arncliffe stand 37	MACMC	Malham Cove	SD897641
Yorks - Malham/ Arncliffe/ Conistone (MAC)	Malham-Arncliffe stand 3	MACTG	Tennant Gill	SD881694
Yorks - Yoredales (YOR)	Yoredale Series stand 6	YORCAM	Cam High Road	SD854840
Yorks - Yoredales (YOR)	Yoredale Series stand 1	YORGR	Greensett	SD747821
Yorks - Yoredales (YOR)	Malham-Arncliffe stand 23	YORHAW	Hawkswick Clowder	SD947687
Yorks - Yoredales (YOR)	Pen-y-Ghent stand 10	YORRG	Rocky Ground	SD863735
Yorks - Yoredales (YOR)	Yoredale Series stand 4	YORWF	Wold Fell	SD791850

2.4 Data Collection

2.4.1 Introduction

The overall rationale for data collection was to establish, through extensive literature searching, those elements of limestone pavement diversity that may contribute to the variations observed in limestone pavements worldwide. Literature review identified that there were numerous aspects of limestone pavement geodiversity, biodiversity, human impact and micro-environment that previous studies have suggested need consideration in order to perform a holistic evaluation of pavement habitats (Brandes, 2000; Burek, 2000; Ford & Williams, 1989; Goldie, 1986; Goldie & Cox, 2000; Trudgill, 1985b; Ward &

Evans, 1976; Webb & Glading, 1998) and these factors are detailed below. The main items that were measured at each site are outlined along with the general approach and protocol for each aspect of the methodology.

Geodiversity: The variables that were considered relevant for examination included *geology* (including age of the limestone, thickness, dip and strike of bedding planes, proximity to a major structural fault, pavement slope, mineral vein intrusion, and fossil presence and type); *geomorphology* (i.e. grike and clint metrics such as width, depth and orientation of grikes and width, length, and perimeter of clints, clint-edge profiles, runnel metrics such as width, length, and frequency and the variety of geomorphological features present); and *pedology* (soil colour, texture, pH and depth in grikes).

Landscape Scale Features: This category included pavement *topography* (including elevation, maritime influence, aspect and landscape) and *local climate* (including frost exposure, precipitation, prevailing wind direction and windspeed).

Biodiversity: Variables considered included *alpha plant diversity* (includes plant species presence per pavement area, abundance and presence of rare species); *plant species height* (includes emergent height and sward height) and *vegetation cover* over a set sample area (see LIS) and *faunal diversity* (macro-fauna present with a more detailed mollusc survey conducted in part).

Human influence: Factors investigated, involving the impact of humans on limestone pavement, were measures of *grazing intensity* (including observation of scats, grazer presence and landowner/farmer interview); *human disturbance* (including litter observed, trampling and accessibility); *pavement disturbance* (damage or removal of clint tops) and *archaeological remains* present on site.

2.5 Geodiversity

2.5.1 <u>Approach to Geodiversity Data Collection</u>

Limestone pavement is a complex karst terrain and previous authors have noted the difficulties of measuring aspects of pavement geodiversity, especially at the larger sites where variation is greatest (e.g. Burek & Conway, 2000a; Waltham & Tillotson, 1989).

For a number of factors included in limestone pavement geodiversity, notably stratigraphy, lithology, structure and pedology, it was necessary to take a pragmatic approach to data collection to take into account the limitations of this study. The multi-faceted, holistic approach to this research meant that it was not practically possible to obtain an in-depth appraisal of every aspect of limestone pavement geodiversity; as this would have involved a considerable amount of additional field equipment and research hours spent on each site. This would have significantly reduced the number of limestone pavements that could have been assessed within the timescale. The approach was therefore to use techniques that could be carried out during the field study and required minimal equipment. Further to this the protocol for geodiversity data collection was adopted from techniques previously developed by expert geologists and geomorphologists; whilst ensuring uniformity and randomisation to avoid bias, e.g. Munsell Color Chart (see Section 2.5.6.1).

Literature review indicated that close examination of the geomorphology of individual pavements was considered key to understanding the critical differences in limestone pavement stands. Goldie (1976) developed a standardised clint and grike measurement methodology in her research, noting that clints are not regular in size and can be extremely complex in shape, with grikes affected by blockages in places not characteristic of the whole grike. She also standardised runnel measurement techniques, and used a refined version of these methods in later studies (Goldie & Cox, 2000). These well-established methods were therefore adopted in this research and the protocol for examining grike, clint and runnel metrics is explained below along with the types of solution feature that were recorded.

Consideration was given to whether a transect or quadrat based approach was the most appropriate. Both were trialled at several sites during the pilot phase of this research. There were a number of problems associated with the quadrat based approach, namely:

- Some sites were too small for an appropriate sized quadrat to be used i.e. less than 20m x 20m in one or all directions.

- Limestone pavements tend to be diverse in shape, with terraced pavements not uncommon. These run along long narrow strips and were therefore considered incompatible with a quadrat approach.
- Thickly wooded pavements can be treacherous and presented considerable practical difficulties in positioning a quadrat.

For these reasons a transect based approach was adopted. To ensure that the positioning of the transect was random the centroid point of the pavement stand (as digitally mapped by the appropriate agency) was used as a consistent marker to locate the start of the transect line. However, it frequently became clear during the course of the research that this centroid point was not a true reflection of the actual centre of the pavement area. Digitisation of habitat mapping was still in its relative infancy within some of the Country Agencies when this protocol was devised and there were still a number of different technical difficulties in their digital mapping techniques (T. Thom, 6th July 2006, pers. comm). To combat this, when the centroid point was patently not near the centre of the stand, a visual centre was estimated by the author and used in its place.

2.5.2 <u>Geology</u>

2.5.2.1 Stratigraphy

The stratigraphy or layering of the rocks had a cyclical sequence which varied according to changes in the sea level, producing various thicknesses of facies. During the period that Carboniferous limestone was formed in Northern Britain and North Wales there were 25-30 cycles in the Asbian (9Ma) with approximately 12 in the Brigantian (6Ma) (Somerville *et al.*, 1986; Vincent, 2004). Vincent cites this as important to the development of limestone pavements, and one of the causes of polygenesis of origin (Vincent, 2004).

The age of the strata at each limestone pavement in this research was investigated by desk-based study using the Digital Geological Map Data of Great Britain provided by the British Geological Survey (obtained from Digimap; http://edina.ac.uk/digimap) in ArcGIS version 9.1 (ESRI;

http://www.esri.com). Nomenclature followed Waters, Browne, Dean and Powell (2007).

2.5.2.2 Lithology

Pavement lithology and the type of formation were researched by desk-based study using the Digital Geological Map Data of Great Britain provided by the British Geological Survey (obtained from Digimap; http://edina.ac.uk/digimap).

Sweeting (1972) emphasised the importance of bedding plane thickness in pavement formation. She summarised that the likeliest limestone pavement formers were more massively bedded areas, possessing a lower frequency of jointing and with a high sparry calcite percentage. These pavements will have lower porosity so are more resistant to solution as they are more crystalline.

Bedding plane thickness was therefore recorded in this study. This was a measure of the overall thickness of bedding planes observed across each pavement site. Where this was variable the range of bedding plane depths was recorded, but the overall coding was given based on the deepest bedding planes visible at each site.

2.5.2.3 Limestone Pavement Structure

Sweeting (1972) stated that the degree of jointing is one of the most important factors affecting the morphology of limestone pavements, citing the work of Wager (1931), who noticed that in Yorkshire the clints are generally rectangular or parallelogram-shaped because of the occurrence of two sets of master joints.

Joints are formed when brittle rock fractures after tectonic disturbance. The frequency of jointing increases near fault lines due to the increased pressure from tectonic movement. Most limestones are non-porous if crystalline, so water passes through by dissolving out the joints, bedding planes and the faults (Taverner, 1981).

Therefore, to estimate tectonic disturbance, the distance of the limestone pavement from the nearest major fault line was calculated using the Digital Geological Map Data of Great Britain provided by the BGS in ArcGIS (obtained from Digimap; http://edina.ac.uk/Digimap).

The dip angle of the bedding plane was assessed across the limestone pavement using a spirit level. This was placed on the top of a minimum of three clint tops and evened out using a clipboard to record the dip, allowing for both the variance in the angle of dip and the maximum dip to be calculated. Dip direction was established using a compass.

2.5.2.4 Mineralisation

Goldie (1976) examined thin sections of pavement limestone from Yorkshire, Cumbria and Switzerland for texture, structure, sparry calcite content, fossil content and associated minerals such as hematite (Fe_2O_3), quartz (SiO_2), gypsum ($CaSO_4{\cdot}2H_2O$) and dolomite ($CaMg(CO_3)_2$). She was unable to demonstrate a conclusive relationship between sparry calcite content and runnel/grike or clint width or depth, but did find that coarser crystalline limestones are connected with a greater number of larger clints than are the finer limestones.

Burek and Conway (2000b) examined soils from limestone pavements in North Wales and related the mineral trace element content such as lead (Pb), zinc (Zn) and copper (Cu), to contamination from the mining histories of the area; and this work was continued by Mitchell (2004). Burek and Conway (2000b) commented that extending this work to limestone pavements across a wider geographical area would offer "help in understanding the development of limestone pavements and their relationship to glacial limits".

These investigations were beyond the scope of this research for reasons previously stated in this chapter (Section 2.5.1), but presence/absence of mineral veins and the frequency of veining was noted at each site, with a field test conducted to establish the mineralogy of the vein.

2.5.2.5 Palaeontology

Detailed study of fossils is complex and beyond the remit of this research, involving consideration of fossil identification, fossil physiology, evolution, energetics, ancient ecological relationships, stratigraphy and diagenetic history (Goldring, 1991). Thus, the aim of recording macrofossil presence and abundance on the limestone pavement sites during field study was primarily to indicate lithological variation between the pavements and to consider the geoconservation value offered by limestone pavements rich in macrofossils in their landscape, educational and aesthetic appeal. The presence, type and abundance of macrofossils were recorded during field study in order to inform geoconservation management.

2.5.3 Landscape Scale Features

A number of elements of the landscape were assessed during the site visits. These included:

- **Altitude** - measured at the centroid point using GPS.
- **Maritime Influence** - assessed by noting whether the sea could be viewed from any part of the pavement and also using Digital Geological Map Data of Great Britain provided by the British Geological Survey in ArcGIS (obtained from Digimap; http://edina.ac.uk/digimap) calculating the distance of pavement to the nearest coastline.
- **Aspect** - where the pavement was sloping the aspect was noted using a compass.
- **Landscape** - a very basic subjective assessment of the pavement as a 'landscape feature' which primarily noted whether the pavement was visible to the public from footpaths or roads, and whether it was deemed visually appealing.

2.5.4 Climate

Much debate has occurred regarding the most important factors in forming karst features; whether it is climate or geology (e.g. Goldie, 1976). The solubility of carbon dioxide decreases with increasing temperature, which has led some writers (e.g. Corbel, 1952) to conclude that "the greatest amount of limestone solution takes place in cold regions". However, the supply of atmospheric carbon dioxide is also important as this is required to produce carbonic acid which is the major attacking agent of the rock. Therefore Goldie (1976) states that others think that the greatest amount of solution occurs in the Tropics where water and CO_2 are most abundant.

Most climatic data for this study were obtained from desk-based research, with the exception of prevailing wind. It included the following:

- **Days of Frost** - Data were obtained from the Meteorological office online resource based on 5km by 5km grid squares, using mean long term annual figures for ground frost (Met. Office, 2009). Incidence of a 'ground frost' refers to a temperature below 0 °C measured on a grass surface. In Northern England, the average number of days with ground frost is on average about 80 days per year on the coast and over 135 days on high ground, with a similar distribution to air frost. Air frost varies from about 30 days a year on the coast to about 55 inland and over 90 in the higher Pennines (Met. Office, 2009).
- **Precipitation** - Data were obtained from the Meteorological Office as long-term UK 5 km x 5 km grid baseline data sets. These are models based on long-term average precipitation rates across the UK, calculated to a 5km grid reference point (Met. Office, 2009).
- **Prevailing Wind** - Calculated on site by assessing any clear orientation in the direction of growth of trees or shrubs on/around the pavement. Where the pavement was open and without trees/shrubs no assessment was possible.
- **Windspeed** - Recorded from the Department for Business Enterprise and Regulatory Reform (BERR) website, using estimates of the annual mean windspeed at 10m above ground level in metres per second (m/s) (Department for Business Enterprise & Regulatory Reform (BERR), 2008), subsequently replaced by DECC (Department of Energy and Climate Change (DECC), 2010). The database uses a 1 kilometre square resolution based on the Ordnance Survey grid system for Great Britain employing an air flow model to estimate the effect of topography on wind speed. However, there is no allowance for the effect of local winds such as sea, mountain or valley breezes and it does not take account of topography on a small scale, or local surface roughness (such as stone walls or trees), which may have a considerable effect on the wind speed, so it can be considered only as a guide (Department of Energy and Climate Change (DECC), 2010).
- **Proximity to Coast** - The proximity of the limestone pavement to the coastal margin, and hence the moderating effect this has on climate, was

estimated by desk-based study using ARCGIS (obtained from Digimap; http://edina.ac.uk/Digimap), as previously mentioned.

2.5.5 Geomorphology

Goldie and Cox (2000) state that there are four natural factors which principally relate to the geomorphology of a limestone pavement area. These are depth and recency of glacial scour, post-glacial solution, tectonic disturbance and lithology. Allied to these, and often the greatest factor, is human disturbance (Goldie & Cox, 2000). Detailed examination of the glacial history of each limestone pavement site was beyond the scope of this research, but a measure of tectonic disturbance was recorded (see Section 2.5.2.3). Investigation of lithological variations in limestone pavements are outlined below along with measures of human influence, both physical (i.e. pavement damage) and biological (e.g. inappropriate grazing management leading to eutrophication).

2.5.5.1 Transect Placement

The starting position of the transect line was the centroid point of the limestone pavement area, as digitally mapped by the appropriate agency - Natural England, YDNPA or CCW. Where this proved impossible or the centroid grid reference was plainly not in the middle of the pavement area, a visual assessment of the centre of the pavement was made and the grid reference taken using GPS (Trimble GeoXT). The GeoXT is a hand held device that has differential GPS capability that gives the user a working accuracy of 0.41m under good satellite configurations (McCaffrey *et al.*, 2005). Transect lines were laid from the centroid point to the edge of the pavement in two directions, north then either to the east or west, whichever offered the greatest distance to the edge of the pavement.

The rationale for recording from the centre of the limestone pavement was for consistency and to avoid edge effects which can influence both geodiversity and biodiversity. For example, Goldie (1976) and Ford and Williams (2007) discuss pressure release forces at the scar edge of a limestone pavement which can significantly widen the associated grikes.

Measurements were taken at regular points along each transect, generally at 5m intervals (2m intervals on smaller pavement stands), see Figure 2-1. The purpose of this was to obtain measurements from distinct and independent grikes and clints. This method incorporated clint and grike measurements from the centre of the pavement going out towards the northern edge of the pavement. In order to ensure that different grikes were sampled (some grikes could be many metres long), measurement alternated between the right side of the transect line (facing towards the end of the transect line) and the left side. A minimum of five grikes were sampled at each limestone pavement, with transect length varying according to length of grikes, as intervals could be greater than 5m apart where grikes were long, in order to avoid re-sampling the same grike.

2.5.5.2 Pavement Slope

Pavement slope was measured using an abney level along the line of maximum slope.

2.5.5.3 Grike Metrics

Grike width, depth and orientation - These parameters were measured at a point that was estimated visually to be midway along the length of the grike at 50mm below the upper surface of the clints. Thus grike width measurement avoided the upper flaring of the grike edge and reflected the width of the lower part of the grike (after Goldie & Cox, 2000). Only grikes that were wider than a fist width (approx. 100mm) were measured for practical reasons. Exceptions were made where the mid-point was not a true representation of the grike width i.e. where the grike had been particularly narrowed or widened at this point. In this instance measurement would then be made close to the mid-point but at a place more representative of the overall grike width. Depth was also measured midway along the length of the grike and measurement taken from the base of the grike to a point level with the upper surface of the clint. Exception was made however if the grike was occluded at this point and a more appropriate place was sought to ensure the depth measurement was representative. Grike orientation was established by compass reading.

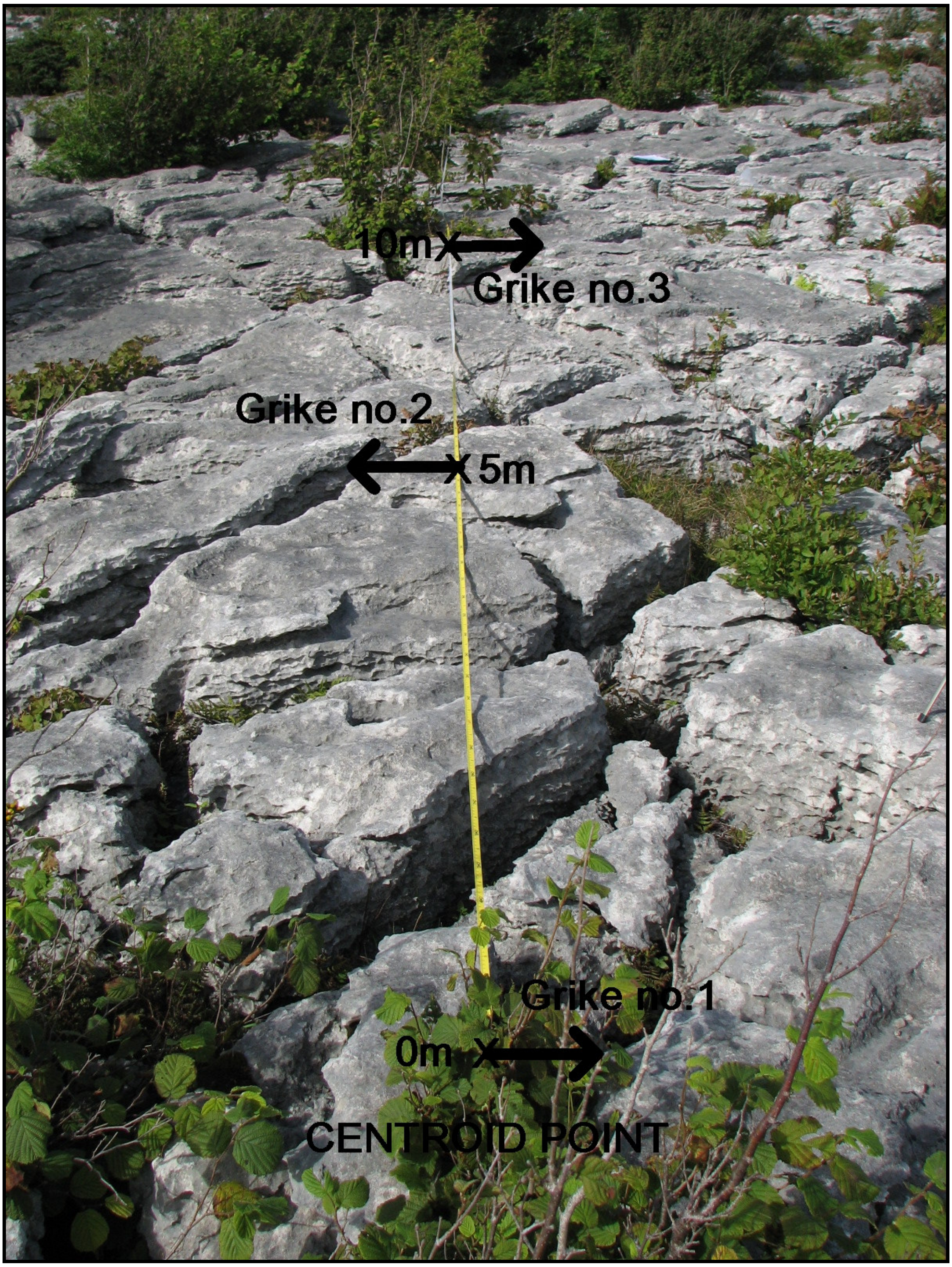

Figure 2-1: This illustrates the methodology that ensured random grike sampling at each pavement stand. Grike no.1 was at 0m (the centroid point), the grike closest to the right hand side of the start of the transect with the clint to the right of this representing clint no.1. At 5m along the transect the grike to the left of the transect line (grike no.2) was measured together with the clint to its left (clint no.2), continuing along the transect line.

2.5.5.4 Clint Metrics

Clint length and width - Clints are often irregular in size and shape so the length measurement was standardised by measuring the longest part of the clint (after Goldie, 1976). Width was then measured perpendicular to the length measurement, at the widest point across the clint, as illustrated in Figure 2-2.

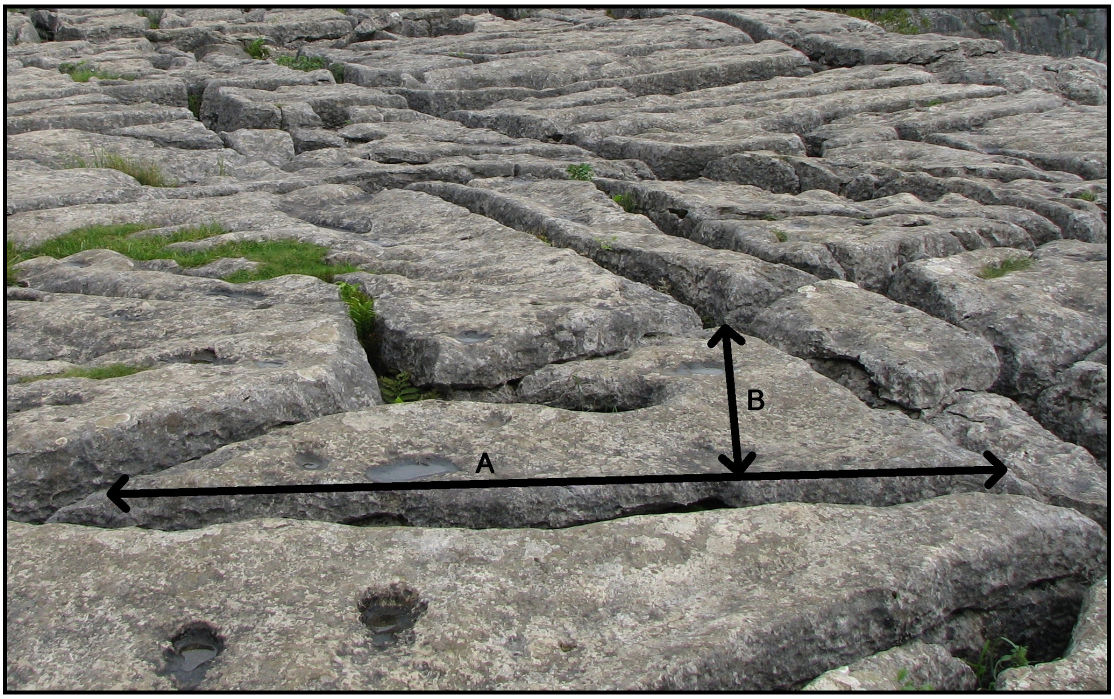

Figure 2-2: Clint length (A) was measured along the longest aspect of the top of the clint. Clint width (B) was then taken at the widest point of the clint, perpendicular to the length measurement.

Clint perimeter - This measurement encompassed the total perimeter of each clint. The measurement was taken 100mm below the upper surface of the clint and the contour of the clint was followed as closely as possible. Thus where there were solution notches or runnels around the perimeter the measurement included these (see Figure 2-3).

Difficulties were encountered in taking this measurement as solutional weathering of the clints often resulted in complex geomorphological variation in the perimeter. Thus it was necessary to ensure that this measurement was always undertaken by the same researcher to ensure consistency of approach.

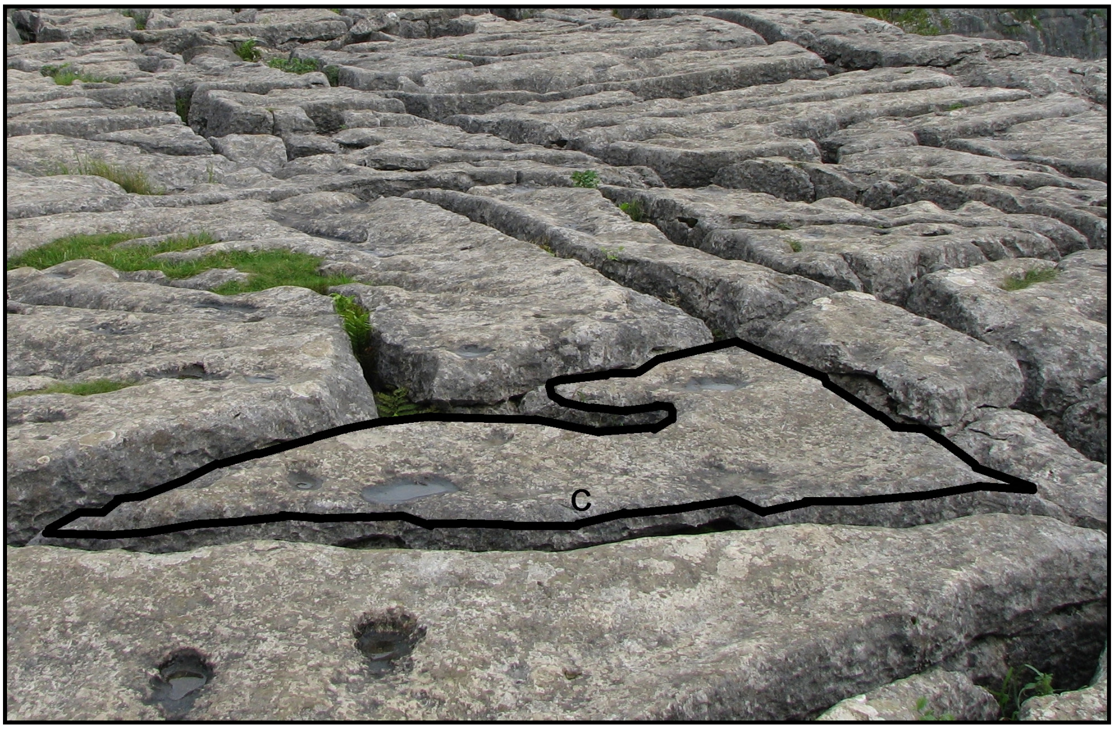

Figure 2-3: Measurement of clint perimeter (C).

Clint edge profile - Roundness of clint edges is a factor generally cited by geomorphologists to denote the amount of weathering on the pavement and the age of the exposure (Goldie, 2006). Measurement of roundness and quantitative assessment of roundness are complicated and from investigation it would seem that to do this properly would require a complex computerised measurement using expensive equipment taken on site (McCarroll, 1992), which was not feasible within this study.

A simple method that can be employed in the field and has been used extensively is Power's 'Scale of Roundness' (Appendix E) (Powers, 1953), based on the Wadell roundness index (Wadell, 1932). This has a simple six point scale to estimate roundness. A carpenter's profile gauge (Figure 2-4) provided an outline of the clint edge, and this was then quantified using the roundness scale.

The evident disadvantage of this methodology is its inherent degree of subjectivity and its lack of sensitivity. To reduce the effects of subjectivity, the author conducted all measurements that were undertaken.

Figure 2-4: Carpenter's profile gauge, used to estimate the degree of roundness of the clint edge. The first three clints were measured at a uniform point and the profile recorded was then compared against Power's 'Scale of Roundness'.

2.5.5.5 Runnel Metrics

Runnel Width and Length - Measurements were taken from the first five runnels that were bisected by the transect line, starting at the centroid point. Runnel width was measured at the widest point along the whole runnel, whilst the length included the total length of each of the five runnels selected.

Runnel Frequency - This was calculated by walking along the northern transect recording the number of runnels bisected wholly or partially by the transect line. The distance measured along the line at the point that the tenth runnel crossed was then recorded. This allowed calculation of average runnel frequency at each site.

2.5.5.6 Geomorphological Features

The presence or absence of pavement features was recorded against a checklist during the general assessment of each pavement. These included:

- solution pans (kamenitzas)
- solution notches
- solution pipes
- runnels (rinnenkarren)
- rills (rillenkarren)
- centripetal runnels
- heelprints (trittkarren)
- solution rippling/honeycomb weathering
- rainpits
- knife-edge clints

- laminated clints
- crenulated sides

A full illustrated guide defining the geomorphological features of limestone pavements was compiled for reference purposes and is included in Appendix F.

2.5.6 <u>Pedology</u>

2.5.6.1 Soil Colour

Colour is a fundamental but variable chemical property of rocks, sediments, soils and is most usually described qualitatively, by visual methods. Developed by Munsell and the U.S.D.A. Soil Conservation Service, the Munsell Color System is generally the field and laboratory standard for classifying soil colour, rocks, and archaeological specimens. This was used in a natural light setting to assess colour of the wet soil sample which was taken from the base of a grike at the centre of the pavement (centroid point) using a 15mm diameter auger.

2.5.6.2 Soil Texture

A uniform assessment of soil texture was made using a soil texture chart (Black, 1997), see Appendix G.

2.5.6.3 Soil Depth

This was recorded within a grike close to the centroid point and at two further random points to the north and the west of each limestone pavement using an auger. The depth measurement was the extent to which the hand-held 15mm diameter auger could be inserted into the ground using 'normal' pressure. The measurement did not include the depth of the grike, only the soil at the base of the grike.

2.5.6.4 Soil pH

Soil pH was assessed using an on-site soil pH field testing kit (Westminster, West Meters Ltd.) which used a colour chart for determining the pH value. Readings were taken from each of the soil samples collected during soil depth measurement using soil at the tip of the auger (deepest soil in the grike) to ensure consistency of sampling methodology. A median value was then calculated from the three measurements and the amount of variability shown by the samples was determined.

2.5.7 Pavement Formation Assessment

Pavement Formation Assessment (PFA) is a method for assessing the quality of the geodiversity on a limestone pavement. It is a new assessment tool for monitoring limestone pavement geodiversity devised in 2007 by Ellis during the monitoring of limestone pavements in the Brecon Beacons, in Wales (G. Ellis, 2007). Initially, Ellis was using the Common Standards Monitoring (CSM) form but it became clear the CSM did not record the structural features of the geology of the limestone areas. Thus the PFA offered a consistent method for recording the condition of the rock outcrop. It is limited in that it is based on direct observation of pavements rather than involving measurement data but it is quick and straight-forward to conduct.

It was decided to trial this when it became available in the second year of fieldwork and the tool was developed, with Ellis, following these trials so that it could be offered to conservation agencies to use in future field surveys. A copy of the revised tool, modified from Ellis's initial PFA, is included in Appendix H.

Further to this the author added a quality rating of the geomorphology of the limestone pavement. This was designed to offer an overall landscape scale indication of the limestone pavement using a five-point scale, where five is the highest quality (Appendix H).

2.6 Biodiversity

2.6.1 Approach to Biodiversity Data Collection

The issue of measuring limestone pavement flora is complex and the 'patchy' distribution of flora nestled in grikes and on clint tops does not lend itself well to the more common approaches to floral assessment; which generally use quadrats and homologous vegetation stands. For example, Rodwell (2000) reviewed the way limestone pavement vegetation was classified, stating that limestone pavement is “frequently described as not fitting the National Vegetation Classification (NVC)”. In this review the team identify pavement vegetation as a “complex of various vegetation types” and classify communities according to their association with each of the elements i.e. deeper grikes; shallower grikes/bigger clint crevices; smaller crevices in grikes and clint surfaces; shallower soil filled crevices; shallower peat-filled grikes; solution-hollows on clint surfaces; seasonally desiccated soils on clint surfaces and pavement surrounds (Rodwell *et al.*, 2000). However, they were unable to come up with a specific classification type for pavement flora in its own right (JNCC, 1998).

In their analysis of limestone pavement flora in the 1970s, Ward and Evans devised a floristic index and categorised pavements into three categories representing pavements with the highest, lower and lowest botanical quality (Ward & Evans, 1976). Their ‘Floristic Index’ classifies plants into nationally rare 'A' species; 'B' species which are nationally uncommon or regional species, 'C' species which are nationally common species and 'D' species i.e. those species whereby the pavement habitat appears to be incidental. The formula used to calculate the index score includes a three point abundance score with rarity based on the Atlas of the British Flora (Perring & Walters, 1962). It was noted that Ward and Evans’ Floristic Index is not adjusted for variation in pavement size. They justify this by stating that because, by their nature, larger pavements will have a greater species count so will be weighted for size in this way.

The approach of Ward and Evans is still well-respected and forms the basis of much of the conservation agencies’ limestone pavement monitoring work across the United Kingdom today. It was therefore decided to use this to provide the framework for the assessment of limestone pavement flora in this research, though with minor adaptations to meet study aims, as outlined below.

2.6.2 Floral Species

Sampling was carried out across the whole limestone pavement stand, a strategy that had the advantage of yielding comprehensive species lists

(McCune & Grace, 2002), which was of additional benefit to the conservation agencies (T. Thom, 6th July 2006, pers. comm.). This approach also had the benefit of including rare and uncommon species, which were of particular interest in this habitat (JNCC, 1998; Thom *et al.*, 2003).

Higher plants, mosses and liverworts were recorded at each limestone pavement by the author in conjunction with a team of botanists experienced in floral surveying. Where possible, a list of those species previously recorded at the site was used as a checklist for the recorders, as recommended under Common Standards Monitoring of limestone pavement (JNCC, 1997). Appendix A details where species lists were available.

All species were noted across the whole site with an indication of whether they were present in grikes or solution cups. Shallow grike species were recorded under 'grike species' as well as those deeper grike species (deemed to be in grikes where depth of grike equals or is greater than twice grike width (Ward & Evans, 1976). Survey time was proportional to the area of the pavement site and was extensive (in excess of 1.5 hours per site), aiming to record the full range of species present. Additional search effort was applied at those sites where surveying was more difficult, such as the heavily wooded pavements (for example Colt Park Wood and Bryn Pydew).

Abundance was recorded by all botanists collaboratively at the end of each survey for each species, using the five point DAFOR scale i.e. Dominant (50-100%); Abundant (30-50%); Frequent (15-30%); Occasional (5-15%) and Rare (<5%).

Small samples of taxa which could not be reliably identified in the field were collected for later examination, along with photographic records of the plant *in situ*. The author was present during all sampling, recording flora on site, aided by other experienced botanists who recorded samples together with the author. Full details of botanists present at each site and dates of visits can be found in Appendix A.

To avoid bias, a plant recording sheet (Appendix I) was used and this was checked thoroughly during each site survey to ensure that more common species were not missed (Ward & Evans, 1975).

2.6.3 Plant Nomenclature

Nomenclature follows Stace (1997) for vascular plants, Smith (2004) for mosses and Paton (1999) for liverworts.

2.6.4 Faunal Species

Figure 2-5: High Brown Fritillary (*Argynnis adippe*), picture courtesy Butterfly Conservation.

Within the pilot phase of this research, techniques were explored for estimating fauna presence on limestone pavement, particularly of those species associated with limestone pavement that have high conservation priority. This included the High Brown Fritillary (Figure 2-5), currently the subject of conservation management strategies on the Morecambe Bay limestone areas (S. Ellis, 2007). It became evident at this stage, however, that exceptionally wet weather allied to lack of specialist faunal knowledge prevented accurate faunal estimates being made.

The approach was therefore to record the presence of fauna on an informal basis only at each pavement. The exception to this was the full mollusc survey carried out by Adrian Norris, an experienced conchologist, with the author, on eleven of the Yorkshire pavement sites.

2.7 Human Influence

2.7.1 Grazing

The presence of fauna grazing on the pavement was recorded including species seen, scats seen and faunal species reported as grazing on the pavement. Intensity was scored as light/medium/heavy by subjective assessment based on evidence seen on site. Evidence included animals seen, scats observed and damage recorded on foliage (bite marks) along with other indicators such as rabbit ‘runs’ and Nettle patches against lee walls (e.g. Figure 2-6). Research conducted by the Limestone Country Project suggested that this method was as robust a methodology as was currently available (Smith *et al.*, 2007). Additionally a telephone interview was conducted with the landowner and management reports on pavement sites were consulted to corroborate the evidence seen (Appendix J).

Figure 2-6: Scats and heavy grazing evident from leaf damage at Smearsett Copys limestone pavement. Pen included for scale.

Grazing levels on limestone pavement are critical, especially sheep grazing, affecting the biodiversity of the pavement (Conway & Onslow, 1999; English Nature, 2004). For this reason there were two further measures recorded as surrogates for grazing intensity - sward height and emergent height. These two aspects have been incorporated into the UK's Common Standards Monitoring methodology for limestone pavements as indicators of grazing intensity (JNCC, 1997) and it therefore was deemed important to examine the relationship between these variables within this holistic research.

2.7.2 Human disturbance

This was an assessment based on numbers of visitors seen on site, accessibility of the site, observed trampling damage to pavement flora or surrounding grasslands and pieces of litter seen on or around the pavement. Accessibility included whether pavement details were available online and/or in an information leaflet.

2.7.3 Disturbance of pavement

This was an assessment of historical damage to the pavement recorded by evidence of clint removal or breakage of the pavement substrate. Previous assessments by Goldie (1994) and Ward and Evans (1975) were also noted in this appraisal. Disturbance was recorded using the 'Pavement Formation Assessment' (after G. Ellis, 2007) which allows the quality of the geomorphology of the pavement and the condition of the pavement to be quantified (see Section 2.5.7 and Appendix H).

2.7.4 <u>Archaeology</u>

There are thousands of kilometres of dry stone walls in the Yorkshire Dales, subdividing the landscape, primarily constructed of limestones. They comprise of stone collected as part of the process of field clearance, extracted from convenient exposures or quarried from small pits adjacent to the line of the wall. Specialist surveys have identified some probable late medieval or early post-medieval boundary walls, constructed of quarried limestone blocks which have been removed from limestone pavement. Walls were also constructed upon the pavement itself as this provided a particularly stable footing (Lord, 2004).

The lime industry was historically important in Britain and recent surveys have indicated that there were over 1,000 lime kilns around Yorkshire and Cumbria (White, 2006). Lime kilns were built to burn limestone and the quicklime produced was then slaked with water to produce calcium hydroxide (slaked lime). This was mostly used to improve grassland by reducing the acidity of the soil but was also an important ingredient in making lime mortar (Johnson, 2002). Remains of these kilns are found adjacent to several pavement sites and they have no doubt impacted on these areas.

Lead mining was also an important factor on some limestone pavements, particularly in North Wales, and this was investigated by Burek and Conway (2000b). This too has impacted and disturbed limestone pavements, e.g. Bryn Alyn in North Wales has an old mine dump below the limestone pavement (Burek & Conway, 2000b).

In this study, recording of archaeological features was restricted to identifying those within an arbitrary 1km radius of the limestone pavement being studied. Only features recognisable to the non-specialist during site surveys were included. Additionally a note was made where limestone walls showed signs that they were constructed from pavement material.

2.8 Line Intercept Sampling

The line intercept sampling (LIS) method, developed in the 1940s, has found important applications in areas such as forestry and wildlife, ecological and biological sciences, and agriculture (Canfield, 1941; Kent & Coker, 1992). LIS is a sampling technique that requires the assessor to make observations along line transects in order to infer the properties of an area. The placement of transects can be chosen in different ways, i.e., randomly or systematically (Catchpole & Catchpole, 1993). It is a methodology which has also been used in the assessment of coral reef systems as it lends itself to the holistic assessment of both substrate and biota (English *et al.*, 1997).

The tool was employed in this research in order to present a 'window in time' of a small area at the centre of each limestone pavement (Figure 2-7). A 10m transect line was systematically positioned across the centroid point of each pavement (see Section 2.5.1) perpendicular to the direction of main grike orientation. Detailed recording was then made of all elements of geodiversity and biodiversity that lay beneath the tape measure, including any tree or shrub canopy present. The LIS was used to estimate the cover of an object or group of objects within a specified area by calculating the fraction of the length of the line that was intercepted by the object. This measure of cover, usually expressed as a percentage, is considered to be an unbiased estimate of the proportion of the total area covered by that object (Catchpole & Catchpole, 1993).

The advantages of this methodology are:

- LIS is a reliable and efficient sampling method for obtaining quantitative percentage cover data.
- LIS can provide detailed information on spatial patterns.
- If the LIS is repeated through time it can provide information on temporal changes.
- LIS requires little equipment and is relatively simple to conduct.

However, disadvantages are:

- Objectives are limited to questions concerning percentage cover data or relative abundance only.

- Comparisons across sites are subject to variations related to the time of year that the LIS is sampled.

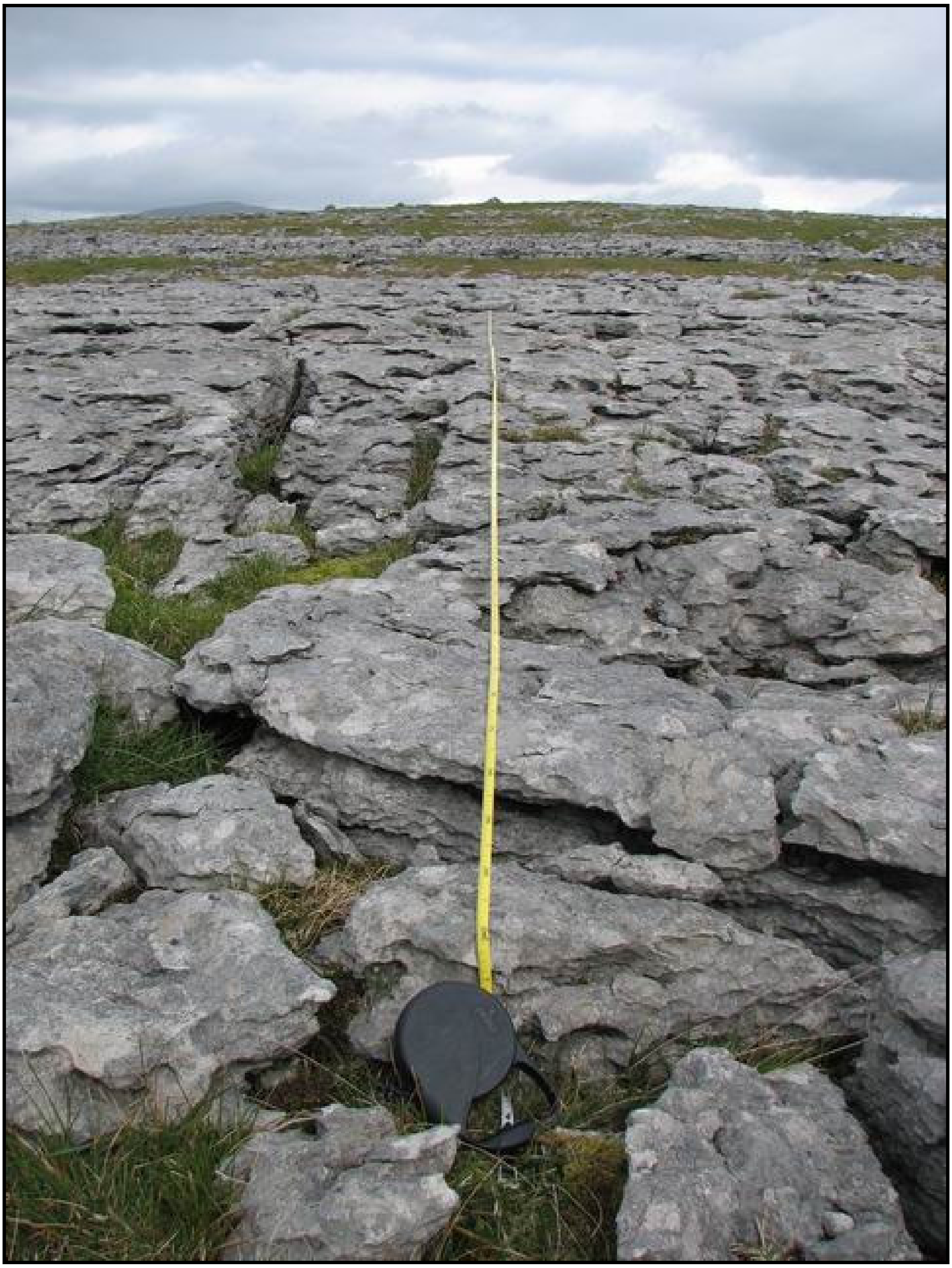

Figure 2-7: LIS provided a detailed picture of a 10m section of the limestone pavement shown here in position at Ewe's Top, Whernside.

2.9 Summary of Methodology

This chapter outlines the field-based research protocol that was adopted in order to examine the critical differences in limestone pavements across the study area. The rationale for obtaining a stratified random sample of limestone pavements across North West England and North Wales is explained and details of the 46 chosen sites are given.

Variables that were measured included elements of geodiversity, landscape scale features, biodiversity and human influence on the limestone pavements. A transect based approach to the measurement of geomorphology was adopted and methods were uniform and consistent. Evidence-based standardised procedures were employed wherever possible. Overall the study devised a new and rigorous methodology which offers a unique contribution to the holistic assessment of limestone pavement for multidisciplinary use.

3 ANALYSIS OF LIMESTONE PAVEMENT GEODIVERSITY

3.1 Introduction

Geodiversity is a word first used in Tasmania in 1993 (Sharples, 1993) and it only became commonly used in the N. Hemisphere in the 21st Century, where Stanley (2000) refined the term, describing geodiversity as "the variety of geological environments, phenomena and processes that make those landscape, rocks, minerals, fossils and soils which provide the framework for life on earth". In 2002, Prosser stated that geodiversity was the "Geological diversity or the variety of rocks, fossils, minerals and natural processes", while Burek's definition also includes soil processes (Burek, 2001). Geomorphology describes the form of the ground surface, the processes that mould it and the history of its development (Ford & Williams, 2007). Sweeting (1966) states that limestone pavements show an "almost infinite morphological variety, with no two outcrops of pavement exactly alike and all are extremely difficult both to map and to classify".

The elements of limestone pavement geodiversity requiring consideration to meet the aims of this project included stratigraphy, lithology, geological structure, mineralisation, palaeontology and geomorphology (Thompson *et al.*, 2006). Added to this were landscape scale features of topography, climate and human influence on the limestone pavement.

The overall approach undertaken to decide which limestone pavement geodiversity variables to assess was outlined in Chapter 2, along with the methods used to measure those variables. The results of the analysis of the data collected are presented in this chapter. All statistical correlations were two-tailed.

3.2 Geology

3.2.1 Stratigraphy

All the limestone pavements studied are of Carboniferous age, laid down between the Chadian and Pendleian (340Ma - 330Ma). The relevant chronostratigraphy during the Lower Carboniferous is presented in Table 3-1.

Table 3-1: Chronostratigraphy from the Lower Carboniferous (Cossey *et al.*, 2004; Thompson *et al.*, 2006)

Age Ma			
327	Lower Carboniferous	Namurian (part)	PENDLEIAN
	Lower Carboniferous	Viséan	BRIGANTIAN
	Lower Carboniferous	Viséan	ASBIAN
	Lower Carboniferous	Viséan	HOLKERIAN
	Lower Carboniferous	Viséan	ARUNDIAN
341	Lower Carboniferous	Viséan / Tournaisian (part)	CHADIAN

Table 3-2 indicates the stratigraphy at each of the 46 limestone pavement stands in the study group. Data from the British Geological Survey (BGS) (obtained from Digimap; http://edina.ac.uk/digimap) showed that these limestone pavements were formed on three major limestone groups, the Great Scar Limestone Group, the Clwyd Group and the Yoredale Group. The Great Scar and the Clwyd Groups are part of the Carboniferous Limestone Supergroup, which is extensive across England and Wales, including south and west Cumbria, the Yorkshire Dales, North and South Wales, the Peak District and the Bristol area (Waters *et al.*, 2007). Distinct from these are six limestone pavements within the study group which originate from the Alston formation within the Yoredale Group, which extends across Northern England and post-dates the Carboniferous Limestone Supergroup.

Table 3-2 (over page): Summary of the age and thickness of the 46 limestone pavements in the study group (BGS data, obtained from Digimap; http://edina.ac.uk/digimap), presented with their coded bed thickness, as measured on site (codes: 1=thinly laminated (<60mm); 2=thickly laminated (60-200mm); 3=very thin (200-600mm); 4=thin (600mm-2m); 5=medium (2-6m))

Site code	Stratigraphy	Lithology	Bedding plane thickness
CUCLO	Brigantian - Arundian	Great Scar Limestone	4
CUGAS	Asbian	Knipe Scar Formation, Great Scar Limestone Group	4
CURA	Asbian	Knipe Scar Formation, Great Scar Limestone Group	4
CUSB	Asbian	Knipe Scar Formation, Great Scar Limestone Group	4
CUSUN	Brigantian - Arundian	Great Scar Limestone Group	4
HRCRAG	Brigantian	Great Scar Limestone Group	5
HRDAL	Brigantian	Great Scar Limestone Group	4
HRHPE	Brigantian	Great Scar Limestone Group	4
HRHPW	Brigantian	Great Scar Limestone Group	4
HRHQ	Brigantian	Great Scar Limestone Group	5
IBCLAP	Asbian	Danny Bridge Formation, Great Scar Limestone Group	3
IBCOLT	Asbian	Danny Bridge Formation, Great Scar Limestone Group	5
IBCRUM	Asbian	Danny Bridge Formation, Great Scar Limestone Group	4
IBSCAR	Asbian	Danny Bridge Formation, Great Scar Limestone Group	5
IBSUL	Asbian	Danny Bridge Formation, Great Scar Limestone Group	4
IBTC	Asbian	Danny Bridge Formation, Great Scar Limestone Group	4
KWPDH	Asbian	Danny Bridge Formation, Great Scar Limestone Group	4
KWPEWE	Asbian	Danny Bridge Formation, Great Scar Limestone Group	5
KWPLS	Asbian - Holkerian	Garsdale Formation, Great Scar Limestone Group	4
KWPOLD	Asbian	Danny Bridge Formation, Great Scar Limestone Group	5
KWPOX	Asbian	Danny Bridge Formation, Great Scar Limestone Group	4
KWPSC	Asbian	Danny Bridge Formation, Great Scar Limestone Group	4
MACBOR	Asbian	Danny Bridge Formation, Great Scar Limestone Group	5
MACBW	Brigantian - Arundian	Great Scar Limestone Group	4
MACHCS	Brigantian - Arundian	Great Scar Limestone Group	4
MACLAN	Brigantian	Gayle Limestone / Alston Formation, Yoredale Group	3
MACLG	Brigantian - Arundian	Great Scar Limestone Group	3
MACMC	Asbian	Danny Bridge Formation, Great Scar Limestone Group	5
MACTG	Asbian	Danny Bridge Formation, Great Scar Limestone Group	4
MBFAR	Brigantian	Great Scar Limestone Group	4
MBGB	Brigantian	Great Scar Limestone Group	5
MBHFA	Brigantian	Great Scar Limestone Group	3
MBHW	Brigantian	Great Scar Limestone Group	4
MBTQ	Brigantian	Great Scar Limestone Group	4
MBUW	Brigantian	Great Scar Limestone Group	4
NWBA	Asbian	Loggerheads Formation, Clwyd Group / Carboniferous Limestone Supergroup	4
NWBON	Brigantian	Clwyd Group, Carboniferous Limestone Supergroup	4
NWBP	Brigantian - Chadian	Clwyd Group, Carboniferous Limestone Supergroup	4
NWGO	Asbian	Loggerheads Formation, Clwyd Group, Carboniferous Limestone Supergroup	3
NWMOE	Brigantian	Clwyd Group, Carboniferous Limestone Supergroup	4
NWTAR	Asbian	Loggerheads Formation, Clwyd Group, Carboniferous Limestone Supergroup	3
YORCAM	Pendleian - Asbian	Alston Formation Main Limestone, Yoredale Group	2
YORGR	Pendleian - Asbian	Alston Formation Main Limestone, Yoredale Group	3
YORHAW	Brigantian	Lower Hawes Limestone / Alston Formation, Yoredale Group	3
YORRG	Pendleian - Asbian	Alston Formation Main Limestone, Yoredale Group	4
YORWF	Pendleian - Asbian	Alston Formation Main Limestone, Yoredale Group	2

3.2.2 Lithology

Lithologically, there are marked variations both within and between the Carboniferous Limestone Group and the Yoredale Group. This is due to the changes in the depositional environment during the Carboniferous period, and consequently facies range between shelf and ramp carbonates within the Carboniferous Limestone Supergroup, whilst the Yoredale Group comprises mixed shelf and deltaic facies (Waters *et al.*, 2007).

The Carboniferous Supergroup is dominated by thick, typically bioclastic to micritic limestones. Within this, the Great Scar Limestone Group comprises highly bioturbated limestones with crinoid banks, shelly or coral biostromes and algal (*Girvanella*) bands (Waters *et al.*, 2007). The Clwyd Limestone Group comprises a diverse range of limestone facies with underlying sandstone and mudstone units (Cossey *et al.*, 2004; Waters *et al.*, 2007). The Clwyd Limestone Group features local dolomitisation, notably at the Great Orme (NWGO), Llandudno, and it also exhibits a high level of secondary mineralisation (Appleton, 1989).

The Yoredale Group comprises alternating conformable thin limestones, mudstones, and thin sandstones, which were laid down in a marine environment, typically in upward coarsening cycles i.e. cyclothems, and the limestone pavement geology varies accordingly (Somerville *et al.*, 1986; Waltham *et al.*, 1997).

The limestone pavements of the Yoredale Group were identified as being distinct from limestone pavements formed on thicker bedded limestones even prior to Ward and Evans' detailed assessment of limestone pavement ecology in the early 1970s (Ward & Evans, 1975). Ward and Evans observed considerable differences in the plant assemblages on the Yoredale pavements during their research and categorised these pavements geologically, unlike the other limestone pavements they studied which Ward and Evans grouped geographically.

Geological mapping has developed since the 1970s, and two of the studied limestone pavements have subsequently been placed within the Alston Formation in the Yoredale Group. These are Langcliffe (Figure 3-1) and Hawkswick Clowder (Figure 3-2).

Figure 3-1: Thin limestones at Langcliffe (MACLAN) form one of the Yoredale Group limestone pavements, on Gayle Limestone, Alston Formation.

Figure 3-2: Hawkswick Clowder (YORHAW), Lower Hawes Limestone, Alston Formation in the Yoredale Group.

3.2.3 Limestone Pavement Structure

Limestone pavements across North-West England and North Wales result not only from their depositional and glacial history but also from their tectonic history, as movement from active fault lines has affected limestone pavement development since the Carboniferous period when the limestones were formed (Waters *et al.*, 2007). In this research, the impact of the tectonic influence on each limestone pavement was estimated by calculating the distance from each site to a major fault line using the Digital Geological Map Data of Great Britain provided by the British Geological Society in ArcGIS (obtained from Digimap; http://edina.ac.uk/digimap) and by measuring pavement dip and direction. The results are presented in Table 3-3 and limestone pavement sites are shown in context with the master fault lines in Figure 3-3 and Figure 3-4.

Table 3-3: Estimated distance of each limestone pavement stand from major fault lines, presented with pavement dip and direction of dip.

Site	Dist to Fault(m)	Dip (degrees)	Dip direction	Site	Dist to Fault(m)	Dip (degrees)	Dip direction
CUCLO	710	7	NE/SW	**MACBW**	1270	12	N/S
CUGAS	6860	14	S/N	**MACHCS**	1835	4	SW/NE
CURA	7500	4	S/N	**MACLAN**	4850	None	None
CUSB	6820	10	SE/NW	**MACLG**	970	17	Variable
CUSUN	6760	None	None	**MACMC**	745	4	SW/NE
HRCRAG	2220	20	W/E	**MACTG**	3260	None	None
HRDAL	1600	10	NE/SW	**MBFAR**	1570	22	SW/NE
HRHPE	1415	25	Variable	**MBGB**	850	10	Variable
HRHPW	600	10	N/S	**MBHFA**	1460	10	W/E
HRHQ	505	5	NE/SW	**MBHW**	1020	13	Variable
IBCLAP	910	6	NW/SE	**MBTQ**	720	40	Variable
IBCOLT	7750	None	None	**MBUW**	1700	10	N/S
IBCRUM	2830	None	None	**NWBA**	100	10	Variable
IBSCAR	5650	None	None	**NWBON**	4200	3	W/E
IBSUL	4625	None	None	**NWBP**	575	16	E/W
IBTC	6840	3	W/E	**NWGO**	3050	15	Variable
KWPDH	4330	2	SW/NE	**NWMOE**	4150	10	W/E
KWPEWE	1450	None	None	**NWTAR**	395	5	SW/NE
KWPLS	1085	10	Variable	**YORCAM**	14350	None	None
KWPOLD	9050	2	SE/NW	**YORGR**	8120	None	None
KWPOX	300	12	Variable	**YORHAW**	3820	2	Variable
KWPSC	30	10	NE/SW	**YORRG**	6865	None	None
MACBOR	260	3	Variable				

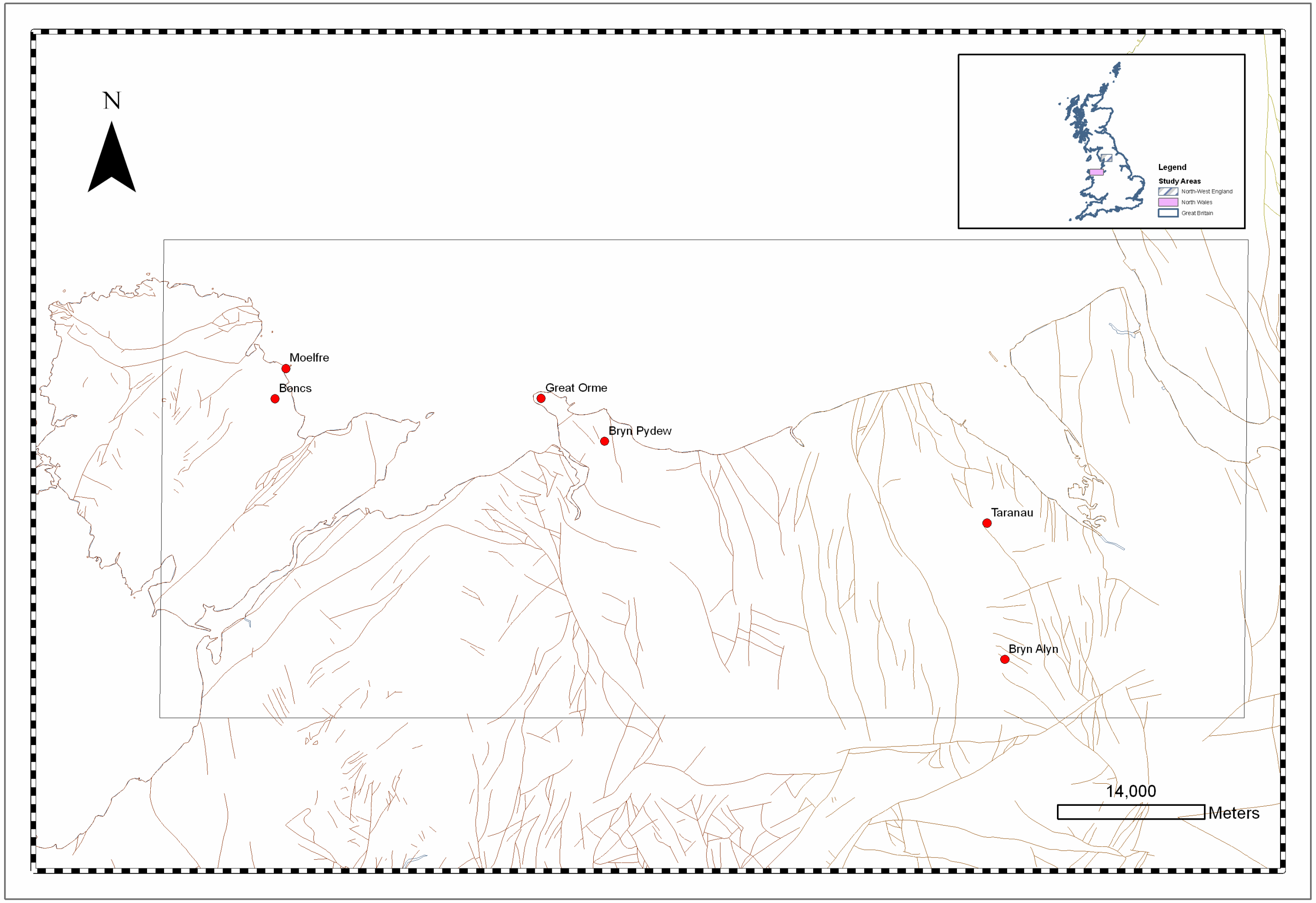

Figure 3-3: Western study area incorporating limestone pavements in North Wales, illustrating major faultlines © Crown copyright/database right 2007. An ordnance Survey/BGS/EDINA supplied service.

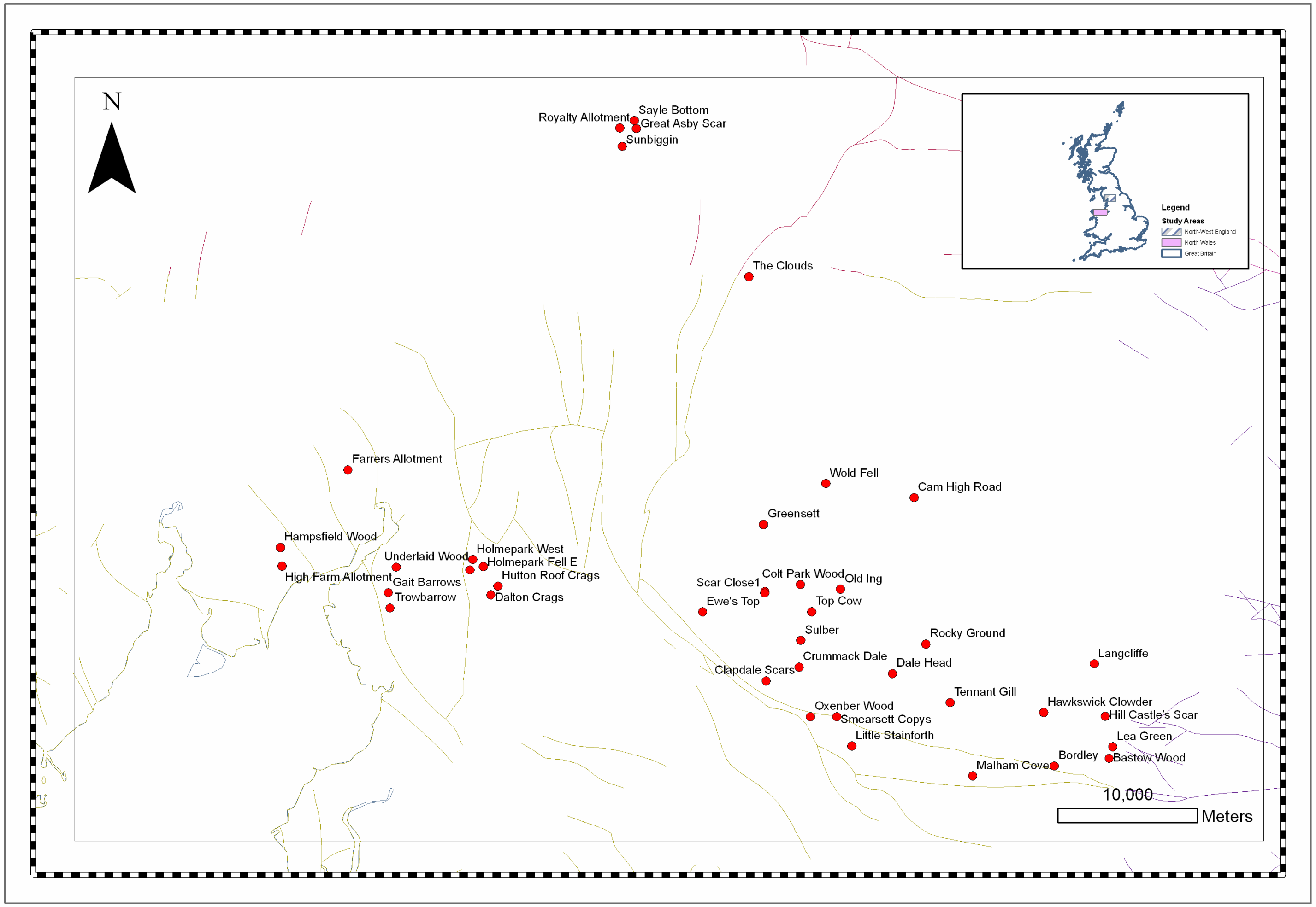

Figure 3-4: Northern study area incorporating limestone pavements in Northern England, illustrating major faultlines © Crown copyright/database right 2007. An ordnance Survey/BGS/EDINA supplied service.

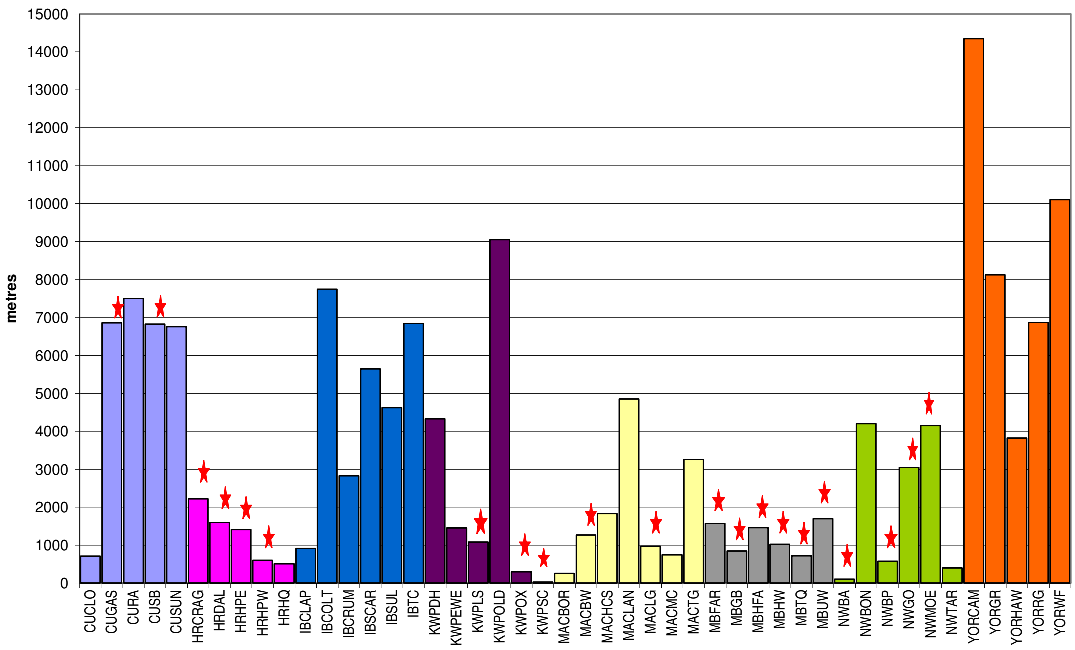

Figure 3-5: Distance of each pavement stand to a major faultline; pavement stands closest to a major fault having the shortest bars. Pavement stands are colour coded by their original sample groups. ★ indicates limestone pavements with a dip greater than 10 degrees.

Normality tests indicated that fault distance measurements did not conform to a normal distribution (Kolmogorov-Smirnov test, $p<0.05$). Where variance and mean are approximately equal, as in this instance, a square root transformation is recommended (Field, 2005) and was applied to the measurement data, which then conformed to normal distribution.

The distance of the limestone pavements from major faults is shown in Figure 3-5. The relationship between distance to fault and limestone pavement dip is also illustrated and it can be seen that pavements closest to a fault are more likely to have a dip of 10° or greater. Correlation of these factors, using transformed fault distance data, resulted in a highly statistically significant negative relationship between distance to fault and limestone pavement dip (Pearson, $r={}^{-}0.329$, $<p=0.05$, $n=46$), indicating that limestone pavement dip increases nearer to a major fault.

The effect of tectonic movement on limestone pavement clint size was also considered by examining the relationship between distance to major fault and clint metrics. Clint width measurement data was not normally distributed and the variance and mean were approximately equal, so square root transformation was recommended (Field, 2005) providing a normal distribution curve (Kolmogorov-Smirnov test, $p>0.05$). Distance to fault and clint width measurements were not statistically significantly positively correlated (Pearson, $r=0.26$, $p=0.08$, $n=46$). Clint length and perimeter data showed variance greater than the mean so logarithmic transformations were employed (Field, 2005) and data sets were reanalysed and found to conform to normality (Kolmogorov-Smirnov test, $p>0.05$). Bivariate correlation of clint length and clint perimeter data with proximity to a fault were both found to be statistically highly significant (Pearson, $r=0.895$, $n=46$ and $r=0.862$, $n=45$ respectively, $p<0.001$) suggesting that clint size decreases closer to a major fault. These results correlate with observations that the frequency of jointing increases near fault lines and results in narrow and sometimes 'knife-like' clints (Jones, 1965; Sweeting, 1972).

Limestone pavements of the Yoredale Group displayed the thinnest bedding planes, with a maximum depth measuring between 0.5m-1.49m (Table 3-2) with the exception of Rocky Ground (YORRG) which had occasional bed thickness of 2.5m, though it should be noted that the majority of the beds at Rocky Ground were much shallower, at around 0.5m. The thickest beds were at Malham Cove limestone pavement with the visible top limestones measuring up to 4m.

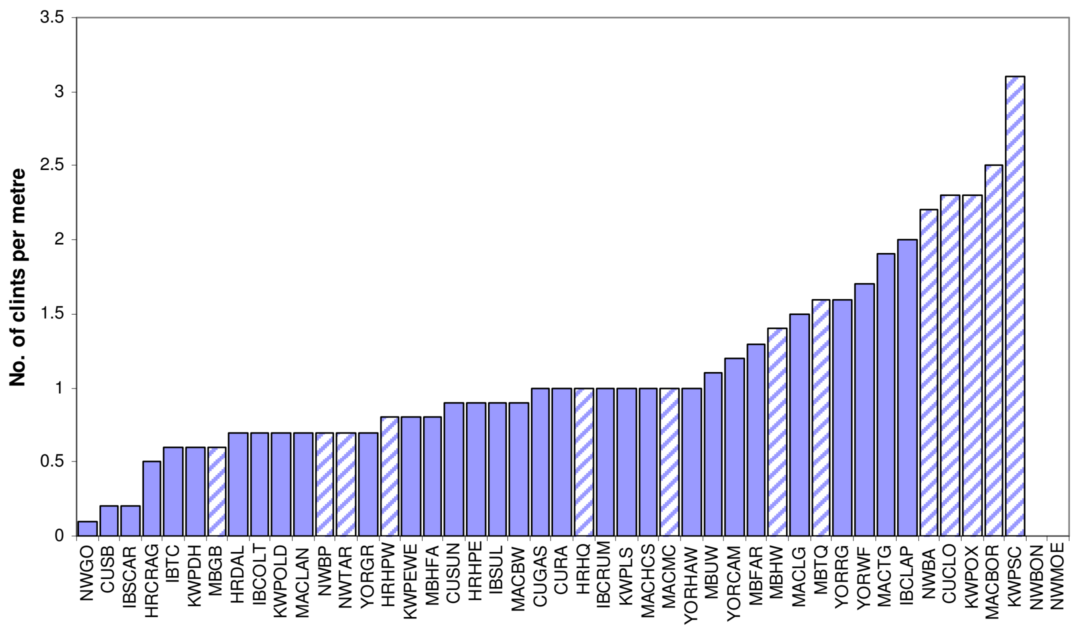

Figure 3-6: Clint frequency at each limestone pavement, presented in ascending order. Diagonal shading indicates pavements that lie within 1000m of a major fault line. No recording was made at two limestone pavements (NWBON and NWMOE).

In order to represent the degree of jointing on the limestone pavement a calculation of the number of clints over a given area was made and this is shown in Figure 3-6. This relationship was analysed (excluding two pavements with no measurement data) using SPSS (SPSS for Windows, 2005).

The clint frequency data collected were normally distributed (Kolmogorov-Smirnov test, $p>0.05$) and these were correlated with square root transformed fault distance data. A highly statistically significant negative relationship was seen ($r=^{-}0.41$, $p<0.01$, $n=44$) suggesting that there is a greater degree of jointing (i.e. smaller clints) on limestone pavements closer to master faults. The R^2 value was 0.17 which indicated that the goodness of fit between these two variables (clint frequency and distance to fault) was low at 17%, concluding that this only explained a part of the complex geodiversity of limestone pavement.

3.2.4 Mineralisation

An indication of the degree of mineralisation at each limestone pavement was assessed by counting the number of mineral veins bisected by the 10m Line Intercept Sample (LIS). The mineralogy of the vein was also tested and in all instances proved to be crystalline calcite, a common component of mineral veins (Figure 3-8), especially those occurring on limestones of Carboniferous age (British Geological Survey, 2004).

Mineralisation is known to increase proximal to a fault (Burek & Conway, 2000b), consequently the relationship between frequency of mineral veins (data conformed to a normal distribution) and the distance from the pavement to a major fault was analysed. A statistically significant positive relationship was seen ($r=0.31$, $p<0.05$, $n=46$) suggesting that there is a greater degree of mineralisation on limestone pavements closer to master faults. Investigating the hypothesis that calcite vein frequency is dependent on distance to fault resulted in a very low R^2 value of 0.1, suggesting that there is some relationship between these variables but it is only part of the complex inter-relationships between the different elements of geodiversity of limestone pavement. Multivariate analysis in Section 5.2.2 examines this further.

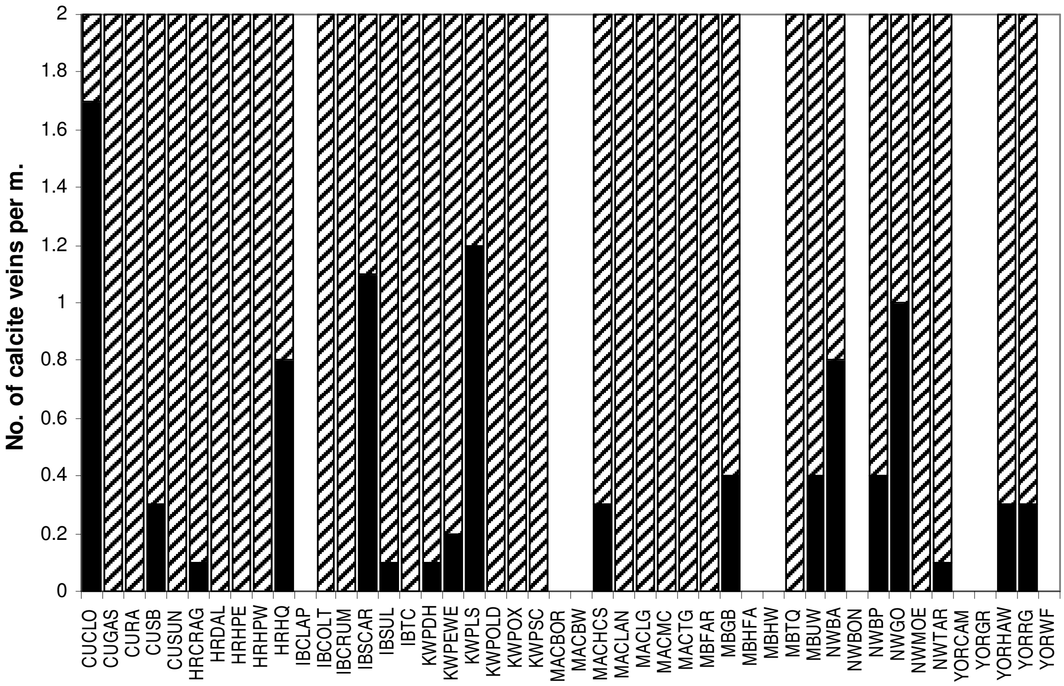

Figure 3-7: Number of calcite veins recorded (black bars) on each limestone pavement, calculated from a 10m transect. Pavements where at least one calcite vein was found are shaded with diagonal bars, showing the nine pavements without visible mineral veining.

Figure 3-8: Mineral vein intrusion visible on a clint top at Scar Close (IBSCAR).

3.2.5 <u>Palaeontology</u>

The results from recording visible fossils at each site are presented in Table 3-4. As previously stated, the wide remit of this study precluded detailed palaeontological examination of the limestones, but did allow fossil presence and type of fossil to be analysed, along with the other elements of geodiversity and biodiversity, to assess which variables were the key drivers of difference in the types of limestone pavements.

Table 3-4: Presence of macrofossils on limestone pavements marked x with approximate frequencies, where 4=abundant; 3=frequent; 2=occasional and 1=rare.

	Fossil type						Fossil type				
Site	Brachiopod	Crinoid	Coral	Bi-valve	**Freq**	**Site**	Brachiopod	Crinoid	Coral	Bi-valve	**Freq**
CUCLO	x				1	**MACBW**					
CUGAS						**MACHCS**					
CURA	x		x		4	**MACLAN**	x				4
CUSB						**MACLG**					
CUSUN	x			x	2	**MACMC**					
HRCRAG			x		2	**MACTG**	x				1
HRDAL			x		1	**MBFAR**					
HRHPE			x		2	**MBGB**					
HRHPW	x		x		4	**MBHFA**					
HRHQ		x			1	**MBHW**					
IBCLAP						**MBTQ**					
IBCOLT						**MBUW**					
IBCRUM						**NWBA**					
IBSCAR		x			1	**NWBON**				x	1
IBSUL						**NWBP**					
IBTC						**NWGO**					
KWPDH						**NWMOE**		x		x	4
KWPEWE	x				2	**NWTAR**		x			1
KWPLS						**YORCAM**	x	x	x		4
KWPOLD						**YORGR**		x			3
KWPOX						**YORHAW**					
KWPSC						**YORRG**					
MACBOR						**YORWF**					

Fossil presence also adds a further dimension of aesthetic and educational appeal which may enhance the geoconservation value of limestone pavement. An example of this is presented in Figure 3-9, recorded on a pavement that was poor in both its geomorphological development and its limestone pavement flora.

Generally, fossils were observed only occasionally during this study, as is illustrated in Table 3-4. This is likely to be because limestone pavements are largely covered with lichens (and mosses/vegetation) which can obscure macrofossils. Differences in facies also account for the variations in fossil presence. The majority of these limestone pavements are formed on the thick shelf limestones of the Carboniferous Limestone Supergroup; facies which are relatively low in biodiversity. Greater biodiversity is to be expected in the deltaic limestones of the Yoredale Group, and this was born out in this investigation.

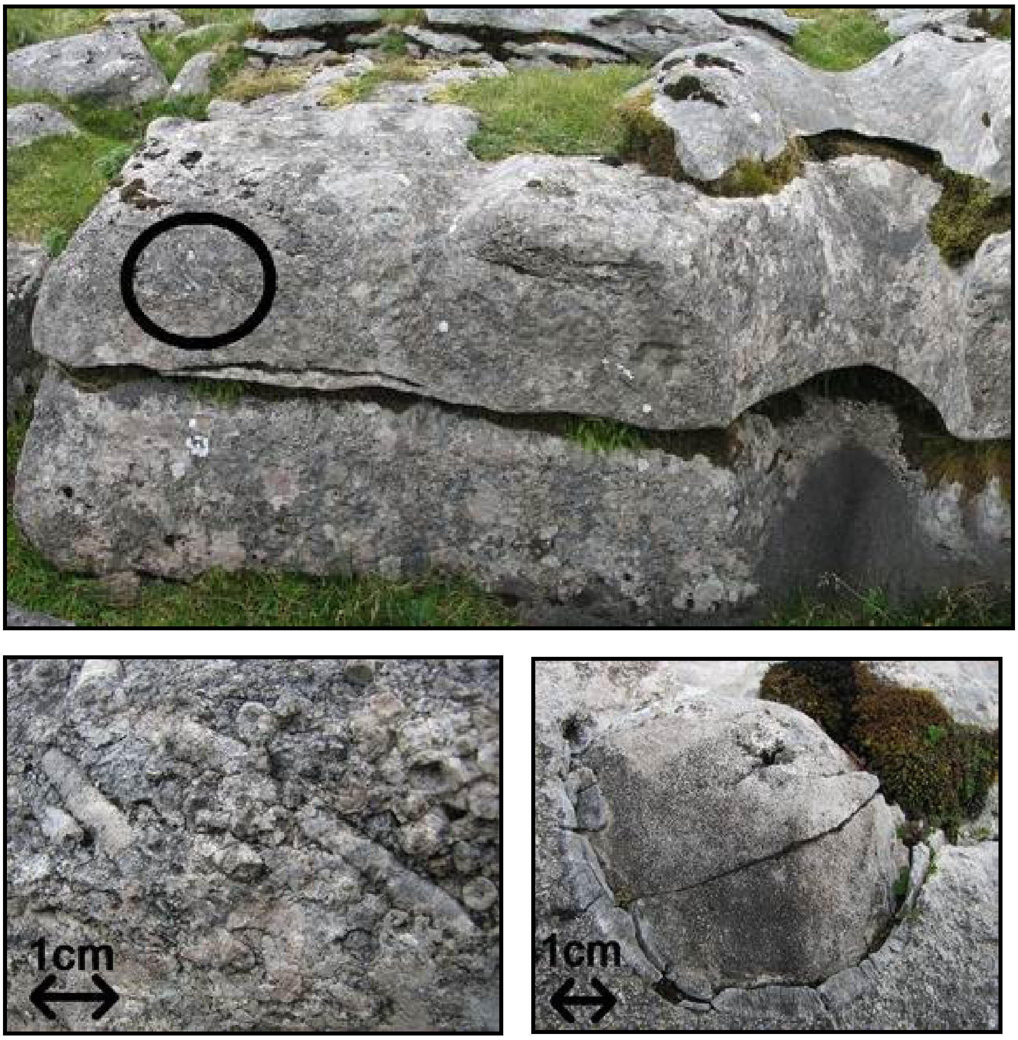

Figure 3-9: A clint at Cam High Road limestone pavement, with crinoid stem fossils indicated, and in close-up below left. Brachiopod fossils, bottom right, were also abundant at this site.

3.3 Landscape Scale Features

3.3.1 Geodiversity and Altitude

The hypothesis that altitude has a significant interplay with both geodiversity and biodiversity of limestone pavements was examined, both in this chapter and the next. The altitude of the 46 limestone pavements, measured at the centroid point of the site, is presented in Figure 3-10. The highest group of pavements were the Yoredales, at a mean altitude 513.6m (+/-84.2m), with Cam High Road the highest at 592m. The Morecambe Bay limestone pavement group were at the lowest altitudes, with a group mean of 119.3m (+/-67.3m). Limestone pavements in North Wales were also generally at lower altitudes, averaging 163.2m (+/-135.9m) which includes the coastal pavement at the lowest altitude of 14m at Moelfre, Anglesey.

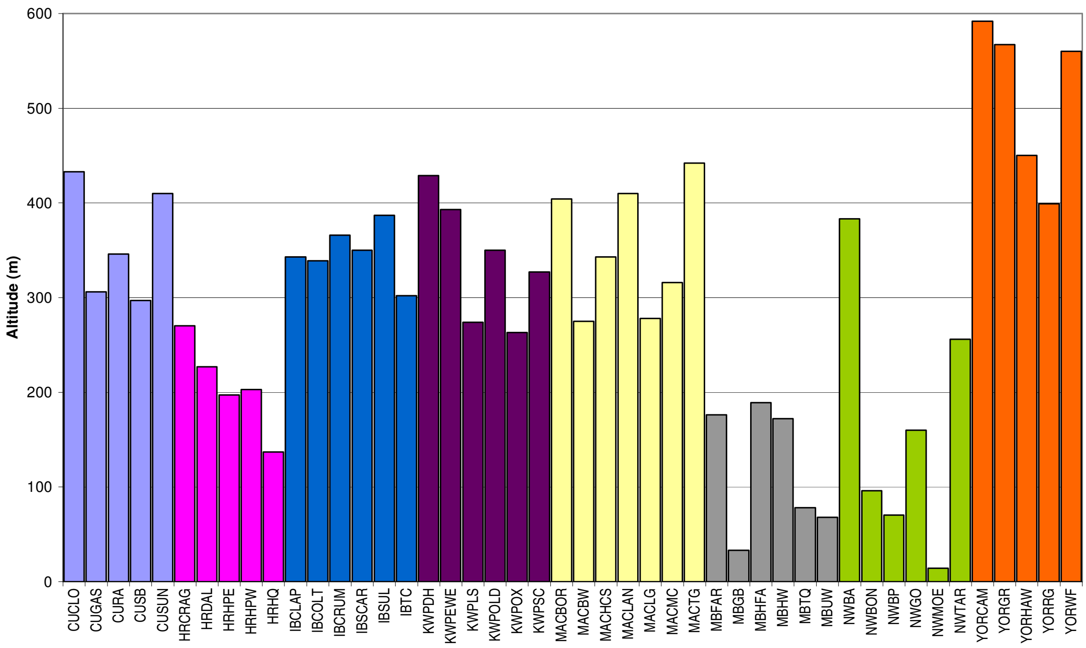

Figure 3-10: Height above sea level of all sites, with pavement stands colour coded by their original sample groups.

Altitude proved a highly significant factor when correlated with other geodiversity variables using Statistical Package for the Social Sciences (SPSS) analytical software (SPSS for Windows, 2005), as can be seen in Table 3-5. Data were transformed, as indicated, when they did not conform to normal distribution (Field, 2005).

Altitude had a highly statistically significant positive correlation with major fault proximity and coast proximity i.e. the higher altitude limestone pavements were associated with greater measured distances from both major faults and the coast.

Table 3-5: Two-tailed Pearson correlation of limestone pavement altitude with geodiversity and climatic variables where ** indicates significance at the 0.01 level and * indicates significance at the 0.05 level (n=46).

ALTITUDE	Fault proximity (square root)	Grike width (mean)	Grike depth (mean)	Clint width (square root)	Log clint length (mean)	Log clint perimeter (mean)	Runnel frequency
Pearson Correlation	.474**	.178	-.333*	-.236	-.266	-.350*	-.388**
	Slope (degrees)	Coast proximity	Area (square root)	Frost days per annum (mean)	Wind speed (mean)	Precipitation per annum (mean)	
Pearson Correlation	-.466**	.718**	.494**	.826**	.328*	.592**	

Altitude was positively correlated with pavement area, days of frost and precipitation (all highly statistically significant) and wind speed, i.e. higher pavements have a significantly greater mean windspeed. Highly statistically significant negative correlation was found between altitude and slope and runnel frequency, showing significant negative correlation with grike depth and clint perimeter.

It is likely that relationships between altitude with clint and grike metrics identified here are spurious, due to the highest limestone pavements in this study being comprised of shallow bedded, friable limestones (Yoredale Group). It is therefore likely that it is the lithology of these limestones that subjects them to increased weathering, resulting in shallower grikes and smaller clints on the limestone pavements at higher altitudes, as discussed in Section 3.2.2.

3.3.2 Topography

Landscape scale features measured at each limestone pavement are summarised in Table 3-6. Maritime influence i.e. the visibility of the coast from the limestone pavement has been presented here as a topographical element, but its moderation of climatic variables is discussed more fully in Section 3.4.

Table 3-6: Summary of the elements of topography assessed at each limestone pavement where x denotes where the feature was present.

Site	Aspect	Maritime influence	Slope direction	Slope (degrees)	Variable slope	Landscape feature
CUCLO	SW		NE-SW	4		x
CUGAS	N		SW-NE	5		x
CURA	N		S-N	4		x
CUSB	NW		SE-NW	5		x
CUSUN	SW		NE-SW	6		x
HRCRAG	E		SW-NE	5		
HRDAL	SW	x	NE-SW	8		
HRHPE	SW	x	NE-SW	6		x
HRHPW	S	x	NW-SE	9		x
HRHQ	W	x	NE-SW	5	x	x
IBCLAP	SE		NW-SE	7		
IBCOLT	-		-	0		x
IBCRUM	SE		NW-SE	9	x	
IBSCAR	-		N-S	1		x
IBSUL	SE		W-E	1		x
IBTC	SE		W-E	3		x
KWPDH	N E		SW-NE	2		x
KWPEWE	-		-	0		x
KWPLS	W		E-W	10	x	
KWPOLD	SW		SE-NW	2		x
KWPOX	N E		SE-NW	6	x	x
KWPSC	SW		SW-NE	20	x	
MACBOR	S		NW-SE	3	x	x
MACBW	S		N-S	6		
MACHCS	N E		SW-NE	4		x
MACLAN	W		-	0		
MACLG	N		SW-NE	5		x
MACMC	N E		SW-NE	4		x
MACTG	-		NW-SE	2		x
MBFAR	N		SE-NW	9		x
MBGB	-		E-W	3	x	
MBHFA	SE	x	NW-SE	6		x
MBHW	N		SW-NE	13	x	
MBTQ	-		E-W	13	x	x
MBUW	SW		NE-SW	4		
NWBA	E		SW-NE	11	x	x
NWBON	E	x	W-E	2		
NWBP	NW	x	NW-SE	14		x
NWGO	SE	x	W-E	9	x	x
NWMOE	E	x	W-E	10		x
NWTAR	SE		SW-NE	5		x
YORCAM	-		-	0		x
YORGR	-		S-N	4		x
YORHAW	NW		SW-NE	2	x	x
YORRG	-		S-N	4		x
YORWF	-		-	0		

3.4 Climatic Variables on Limestone Pavement

Climatic variables at each limestone pavement are presented here. Ground frost and precipitation data are taken from Met Office long term annual means (Met. Office, 2009) with windspeed calculated using BERR windspeed modelling figures (Department for Business Enterprise & Regulatory Reform (BERR), 2008), now at the Department of Energy and Climate Change (DECC) (Department of Energy and Climate Change (DECC), 2010). Climate data relates to the British National Grid 5km grid square that contains the limestone pavement site, and is summarised in Table 3-7. It can be seen that climatic variables closely inter-relate with each other, with higher levels of precipitation and annual days of ground frost all positively associated with limestone pavements at higher altitudes (Table 3-8). The moderating influence of the coast on the climate can also be identified with highly statistically significantly lower precipitation and frost days on limestone pavements closer to the sea (Table 3-8).

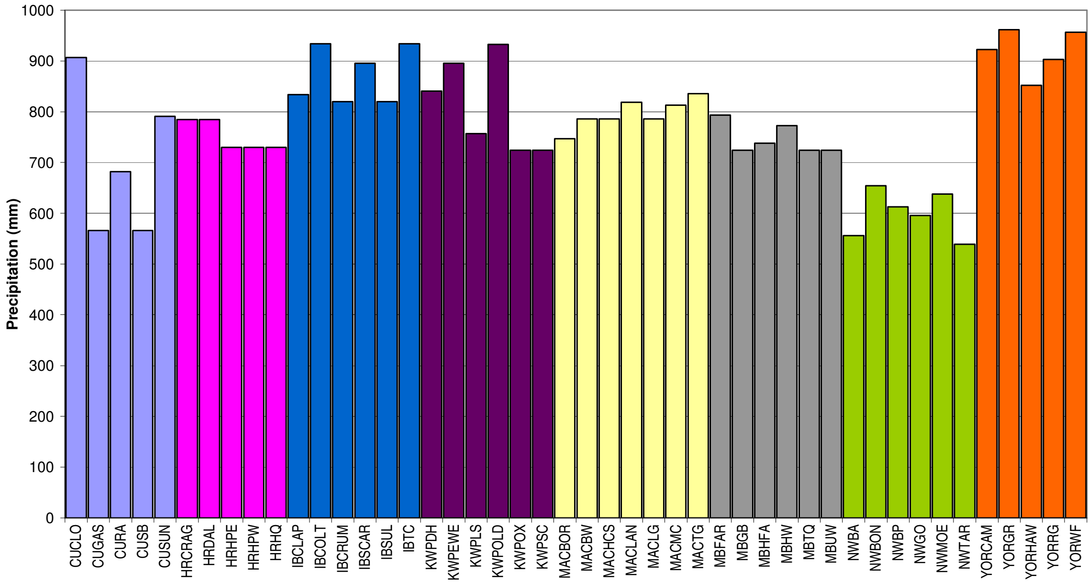

Figure 3-11: Mean annual precipitation, with pavement stands colour coded by their original sample groups.

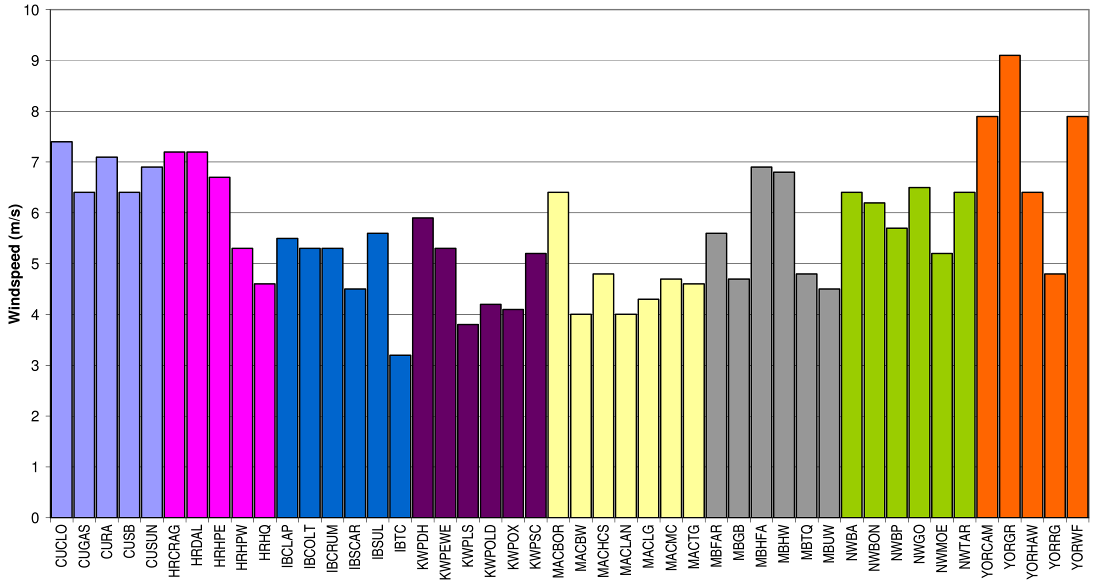

Figure 3-12: Windspeed (in metres/second), with pavement stands colour coded by their original sample groups.

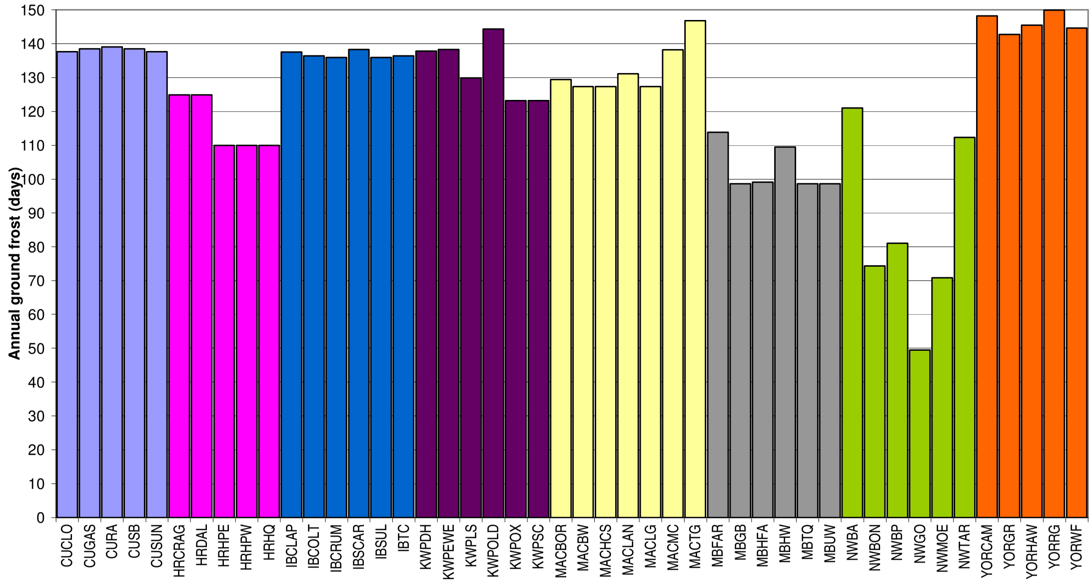

Figure 3-13: Long term average days of ground frost per annum, with pavement stands colour coded by their original sample groups.

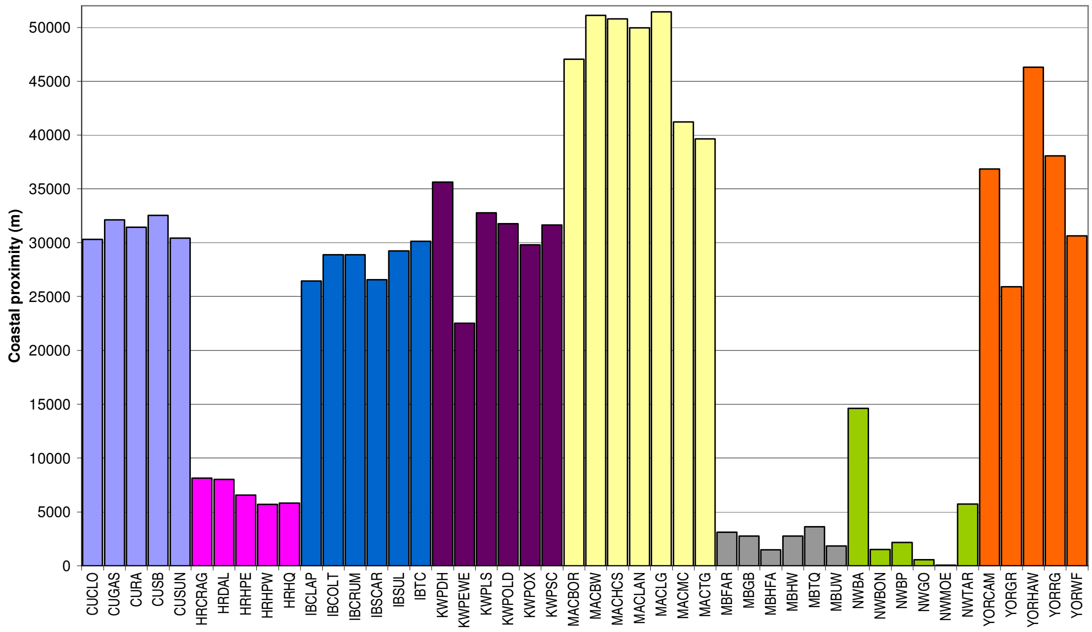

Figure 3-14: Distance of pavement stand from coast, with pavement stands colour coded by their original sample groups.

Table 3-7: Mean annual figures for ground frost, precipitation and windspeed calculated from data courtesy of Met Office (Met. Office, 2009) and BERR (Department for Business Enterprise & Regulatory Reform (BERR), 2008 [now DECC]). Figures relate to the 5km grid square containing the limestone pavement site.

Site	Mean annual ground frost (days)	Mean annual precipitation (mm)	Prevailing wind	Windspeed (m/s) at 10m above ground level
CUCLO	138	907	none	7.4
CUGAS	139	566	none	6.4
CURA	139	682	SW	7.1
CUSB	139	566	SE	6.4
CUSUN	138	791	SW	6.9
HRCRAG	125	785	SW	7.2
HRDAL	125	785	none	7.2
HRHPE	110	730	W	6.7
HRHPW	110	730	NW	5.3
HRHQ	110	730	SW	4.6
IBCLAP	138	834	none	5.5
IBCOLT	136	934	none	5.3
IBCRUM	136	820	W	5.3
IBSCAR	138	896	none	4.5
IBSUL	136	820	NW	5.6
IBTC	136	934	NW	3.2
KWPDH	138	841	n/k	5.9
KWPEWE	138	896	N	5.3
KWPLS	130	757	W	3.8
KWPOLD	144	933	W	4.2
KWPOX	123	724	none	4.1
KWPSC	123	724	n/k	5.2
MACBOR	129	747	NE	6.4
MACBW	127	786	none	4
MACHCS	127	786	W	4.8

Site	Mean annual ground frost (days)	Mean annual precipitation (mm)	Prevailing wind	Windspeed (m/s) at 10m above ground level
MACLG	127	786	none	4.3
MACMC	138	813	S	4.7
MACTG	147	836	n/k	4.6
MBFAR	114	794	SW	5.6
MBGB	99	724	none	4.7
MBHFA	99	738	NW	6.9
MBHW	110	773	none	6.8
MBTQ	99	724	none	4.8
MBUW	99	724	none	4.5
NWBA	121	556	NE	6.4
NWBON	74	654	none	6.2
NWBP	81	613	none	5.7
NWGO	49	596	NW	6.5
NWMOE	71	638*nearest	N	5.2
NWTAR	112	539	none	6.4
YORCAM	148	923	W	7.9
YORGR	143	962	W	9.1
YORHAW	145	852	n/k	6.4
YORRG	150	903	W	4.8
YORWF	145	957	W	7.9

Table 3-8: Two-tailed Spearman correlation geodiversity and climatic variables where ** indicates significance at the 0.01 level and * indicates significance at the 0.05 level, n=46.

	Grike width	Grike depth	Soil depth	Altitude	Proximity to coast	Precipitation	Sward height	Runnel frequency	Frost days	Dip	Slope
Precip-itation	.30*	⁻.11	.36*	.68**	.42**	1.0	⁻.39**	⁻.23	.67**	⁻.54**	⁻.59**
Frost days	.19	⁻.09	.46**	.86**	.71**	.67**	⁻.57**	⁻.26	1.0	⁻.57**	⁻.59**

3.5 Geomorphology

Results presented here include grike, clint and runnel metrics and analysis of the other geomorphological features recorded at each site. Outcomes from a new pilot measure for describing and monitoring limestone pavement, ‘Pavement Formation Assessment’ (G. Ellis, 2007) (Appendix H) are also displayed.

3.5.1 Grike Width and Depth

Descriptive statistics were calculated from grike metrics for each limestone pavement and are presented in Figure 3-15. Scar Close (IBSCAR) limestone pavement in the Ingleborough National Nature Reserve, North Yorkshire, had the greatest mean grike depth at 1.87m and also the highest standard deviation around the mean of the ten grikes measured, at +/- 0.78m, with grike depths ranging from 0.77m to 3.4m. Mean grike depths were lowest in the Yoredale limestone pavement group with the shallowest mean grike depth of 200mm (+/- 48mm) measured at Greensett (YORGR).

Mean grike depths across limestone pavements using the Ward and Evans geographical/lithological grouping are presented in Table 3-9. The Yoredale limestone pavements have a low mean grike depth (380mm +/-160mm), reflecting the thin bedding planes in the lithology of the Yoredale Group which comprise alternate limestones, mudstones and sandstones. The pavements of North Wales are also relatively shallow, averaging just over 0.5m depth.

Table 3-9: Mean grike depths and widths with standard deviation in each of the Ward and Evans (1975) pavement groupings, measured in metres. Pavement group codes are Cumbria (CU), Hutton Roof (HR), Ingleborough (IB), Kingsdale/Whernside/Pen-y-Ghent (KWP), Malham/Arncliffe/Conistone (MAC), Morecambe Bay (MB), North Wales (NW) and Yoredale series (YOR).

	CU	HR	IB	KWP	MAC	MB	NW	YOR
Mean grike depth	0.79	1.04	0.97	0.64	0.72	0.93	0.56	0.38
Depth s.d.	0.12	0.31	0.48	0.10	0.41	0.49	0.15	0.16
Mean grike width	0.17	0.23	0.24	0.23	0.19	0.15	0.24	0.29
Width s.d.	0.05	0.09	0.13	0.17	0.07	0.02	0.08	0.10

Mean grike width was measured as widest at Old Ing limestone pavement (KWPOLD), one of the Pen-y-Ghent limestone pavements, at 0.54m +/- 0.32m. Generally, however, the Yoredale Group limestone pavements had the widest as well as the shallowest grikes (Table 3-9). A typical example of limestone pavement in the Yoredale Group is shown in Figure 3-16, illustrating the wide, shallow grikes with clints that perch like islands in a limestone grassland.

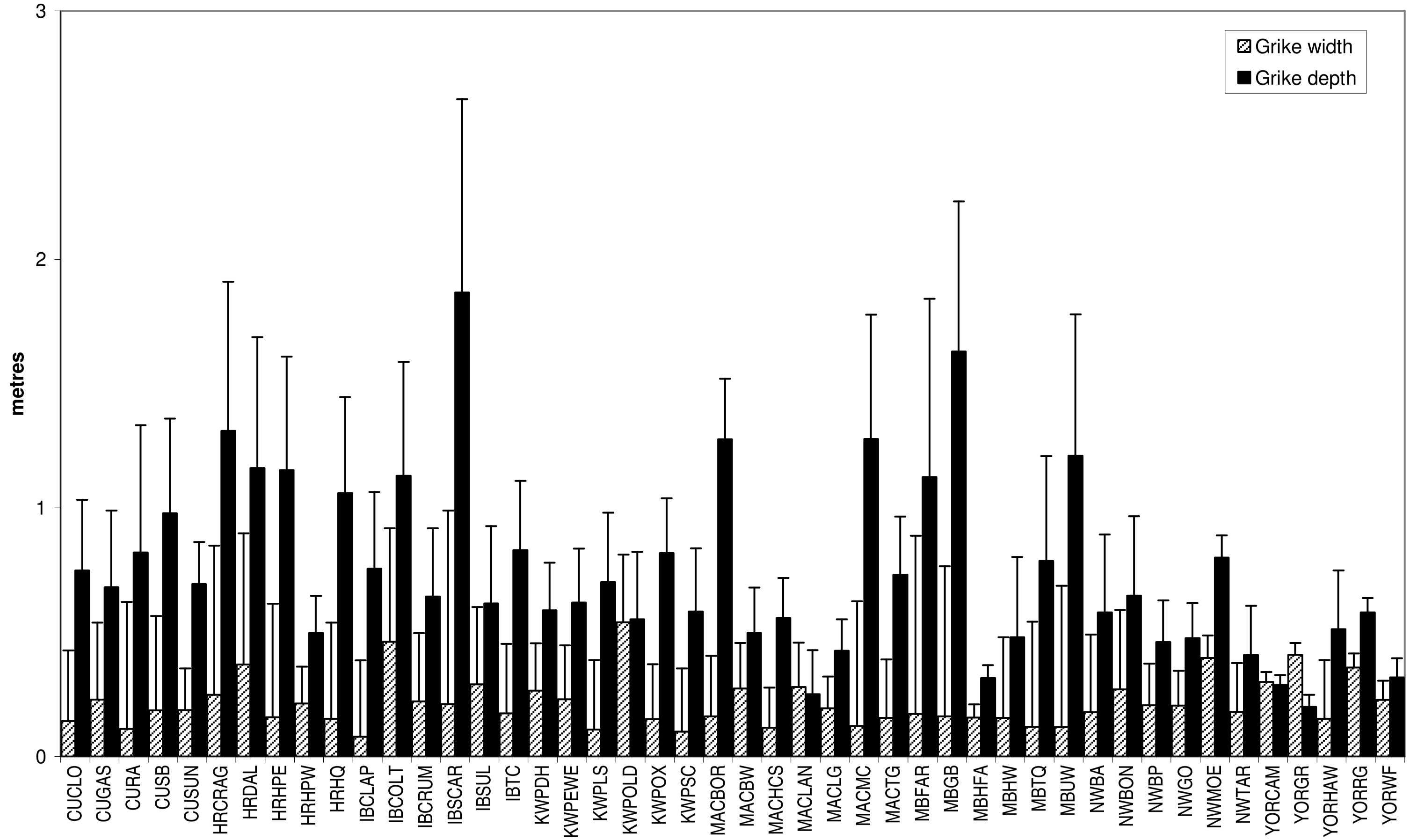

Figure 3-15: Mean grike width and depth recorded at each limestone pavement. Standard deviation indicated by positive error bars.

Figure 3-16: Cam High Road, Coverdale, one of the limestone pavements in the Yoredale Group. Pavement is very well dissected with wide grikes and small 'flaky' clints that sit like islands in the limestone grassland.

3.5.2 Grike Orientation

The major orientation of the grikes at each limestone pavement was recorded at the 46 sites and is presented in Figure 3-17 and Figure 3-18 .

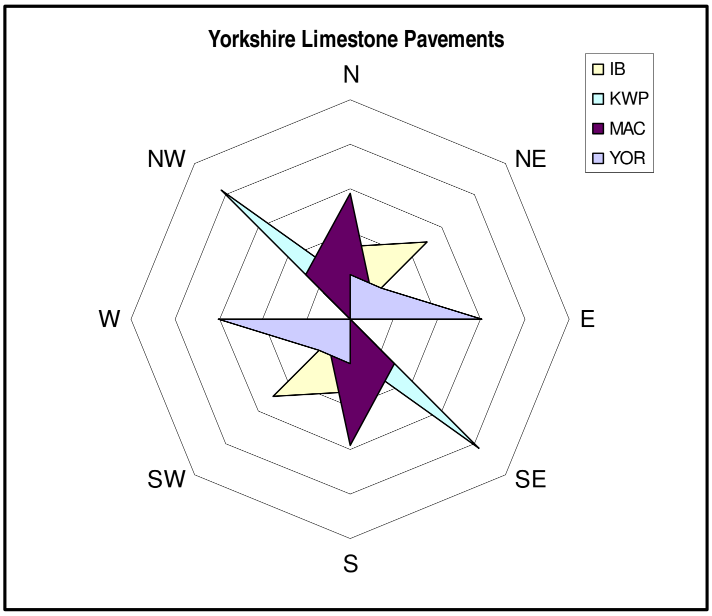

Figure 3-17: Main grike orientation observed on the four Yorkshire Groups (see legend for coding).

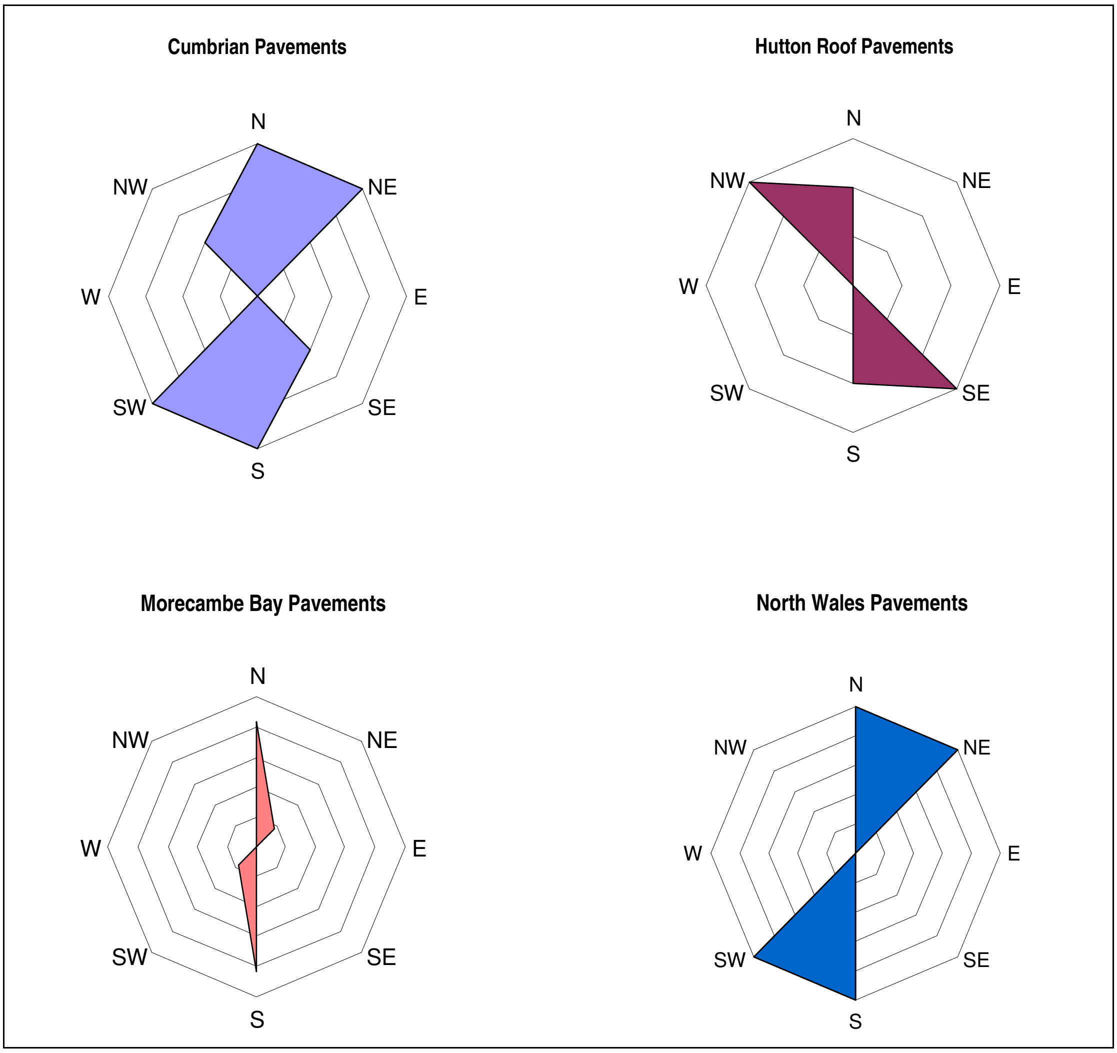

Figure 3-18: Main grike orientation observed in the Cumbrian, Lancastrian and Welsh limestone pavements.

3.5.3 Clint Length, Width and Perimeter

The measurement of clint length and perimeter proved difficult at some sites. This was where deep runnelling on thick bedding planes created large expanses of exposed clint surface with indistinct definition between deep runnels and grikes. Additionally, some pavements had strong uni-directional dissection, resulting in linear clints many metres long with dendroid surface morphology. Measuring clint metrics proved particularly challenging at Dale Head (KWPDH), Great Orme (NWGO), Sayle Bottom (CUSB) on Great Asby Scar and Scar Close (IBSCAR). In all instances the approach to obtaining robust data was consistency in the recorder whilst following the methodology protocol as closely as was feasible.

Further difficulties in estimating clint metrics were experienced on wooded limestone pavements, where clint edges were masked in vegetation. This was particularly notable at Hampsfield Wood (MBHW), on the Grange pavements, and Boncs (NWBON) on Anglesey.

Clint metrics are summarised in Figure 3-21. Clint metric data did not conform to a normal distribution (Kolmogorov-Smirnov test, $p<0.05$) and was therefore transformed as described in Section 3.2.3. All data sets were reanalysed and then conformed to normality (Kolmogorov-Smirnov test, $p>0.05$). Clint size, i.e. width, length and perimeter, had statistically significant positive relationships with grike depth (Pearson, $r=0.329$, $n=46$; $r=0.343$, $n=46$ and $r=0.376$, $n=45$ respectively, $p<0.05$), indicating that pavements with deeper grikes have larger clints.

Scar Close had the largest clints of all the limestone pavements assessed, ranging between 0.66-12m in width and 1.9-39.9m in length. In contrast to this, the smallest clints were measured at The Clouds (CUCLO), Kirkby Stephen, with width ranging from 90-620mm (mean 323mm +/-165mm) and length from 650-4800mm (mean 1224mm, +/-1274mm). The relationship between clint size and limestone pavement structure proved significant, with smaller clints associated with tectonic movement (i.e. proximal to a major fault), and this is presented in Section 3.2.3.

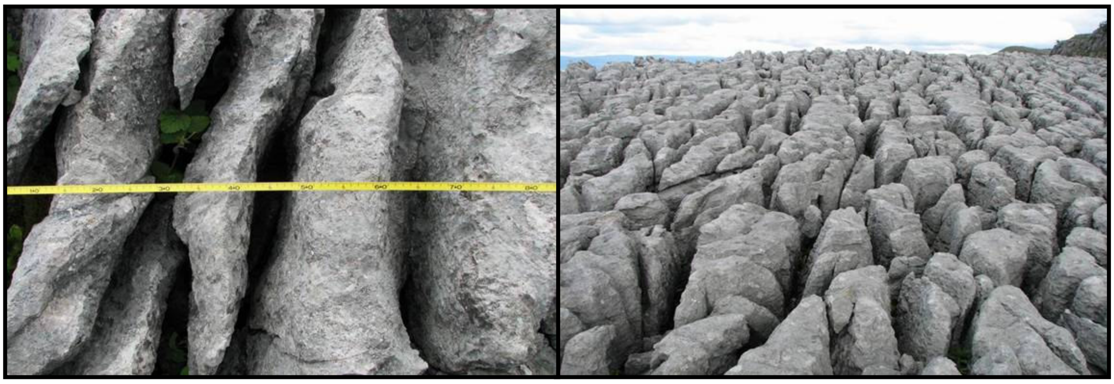

Figure 3-19 Close-up of 'knife-like' clints at Fell End Clouds, with tape measure (left) indicating their narrowness, with full pavement stand pictured right.

Clint perimeter measurements from 43 of the limestone pavements studied are presented in Figure 3-20. Great Orme and Scar Close clint perimeters were exceptionally large and have been omitted to assist clear presentation.

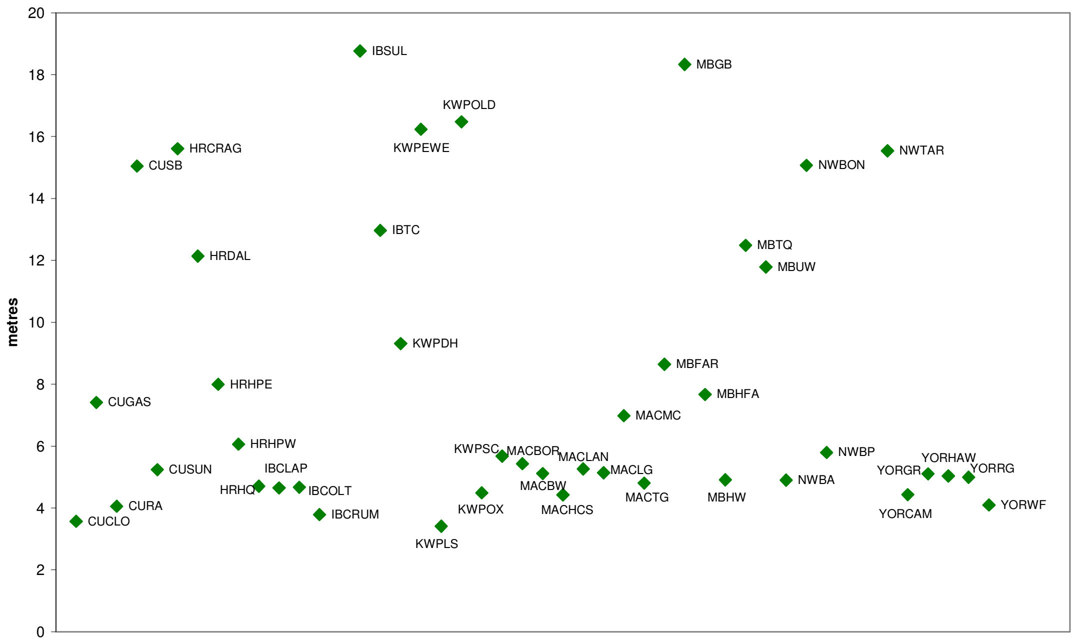

Figure 3-20: Chart providing mean clint perimeter dimensions. Horizontal axis is for illustration only, pavements presented alphabetically. Outliers have been omitted, namely Great Orme at 64.26m (+/-66.40m) and Scar Close at 59.99m (+/-50.95m). No measurement was made at Moelfre, on Anglesey.

3.5.4 <u>Clint Edge Profile</u>

Measurement was conducted using the carpenter's gauge at just over half of the limestone pavements and the clint edge profile was estimated using Power's 'Scale of Roundness' (Powers, 1953) (see Appendix E). Results were extremely variable, with only one site recording a consistent score for each of the three clints assessed. This suggests that a revised methodology is required to effectively analyse and draw any valid conclusions regarding the clint edge profile on limestone pavements.

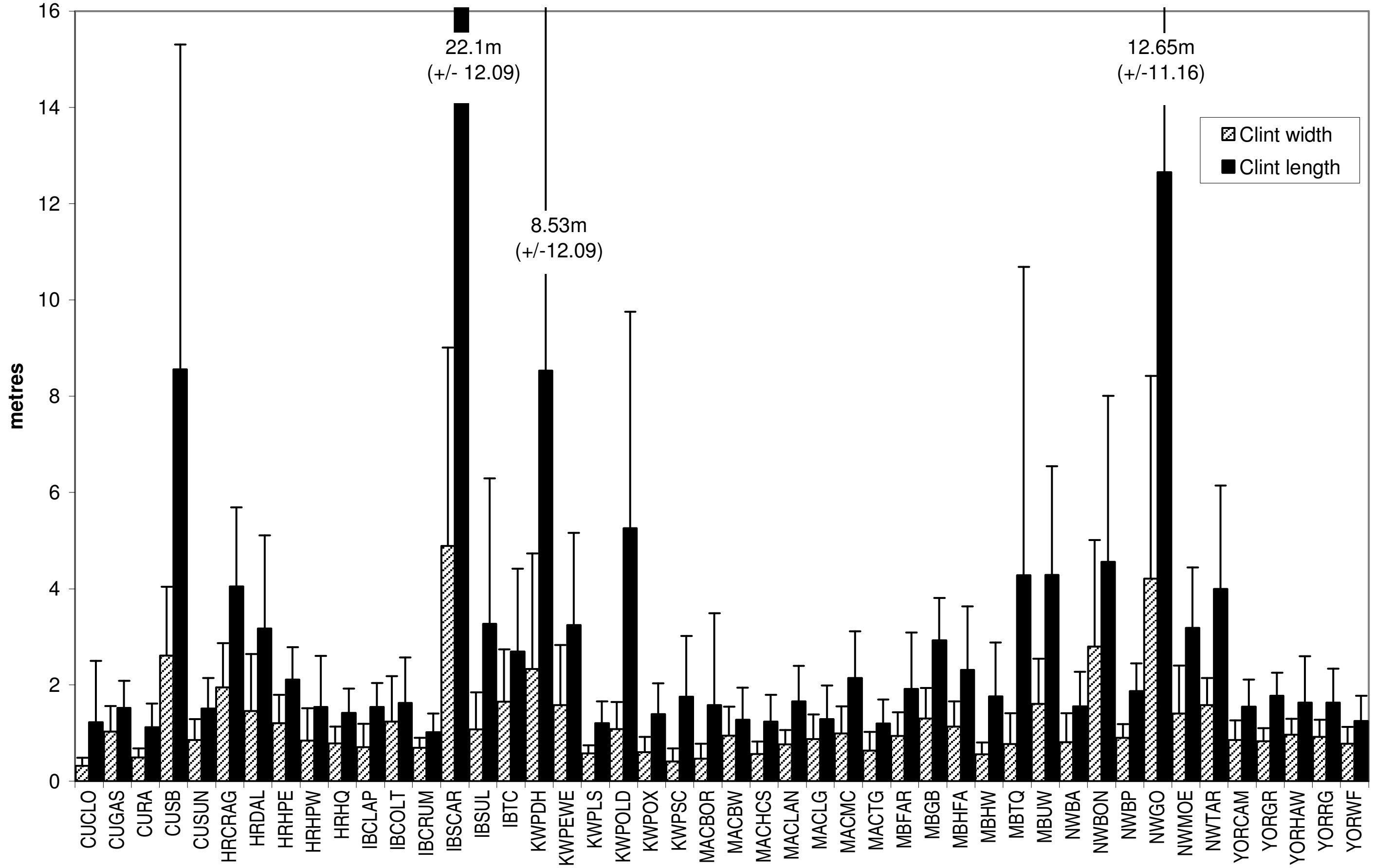

Figure 3-21: Mean clint width and length at each limestone pavement with standard deviation indicated by positive error bars. It should be noted that Scar Close (IBSCAR) had an exceptionally large mean clint length, with two other pavements having large variability around the mean in clint lengths, namely Dale Head (KWPDH) and Great Orme (NWGO).

3.5.5 Runnel Width, Length and Frequency

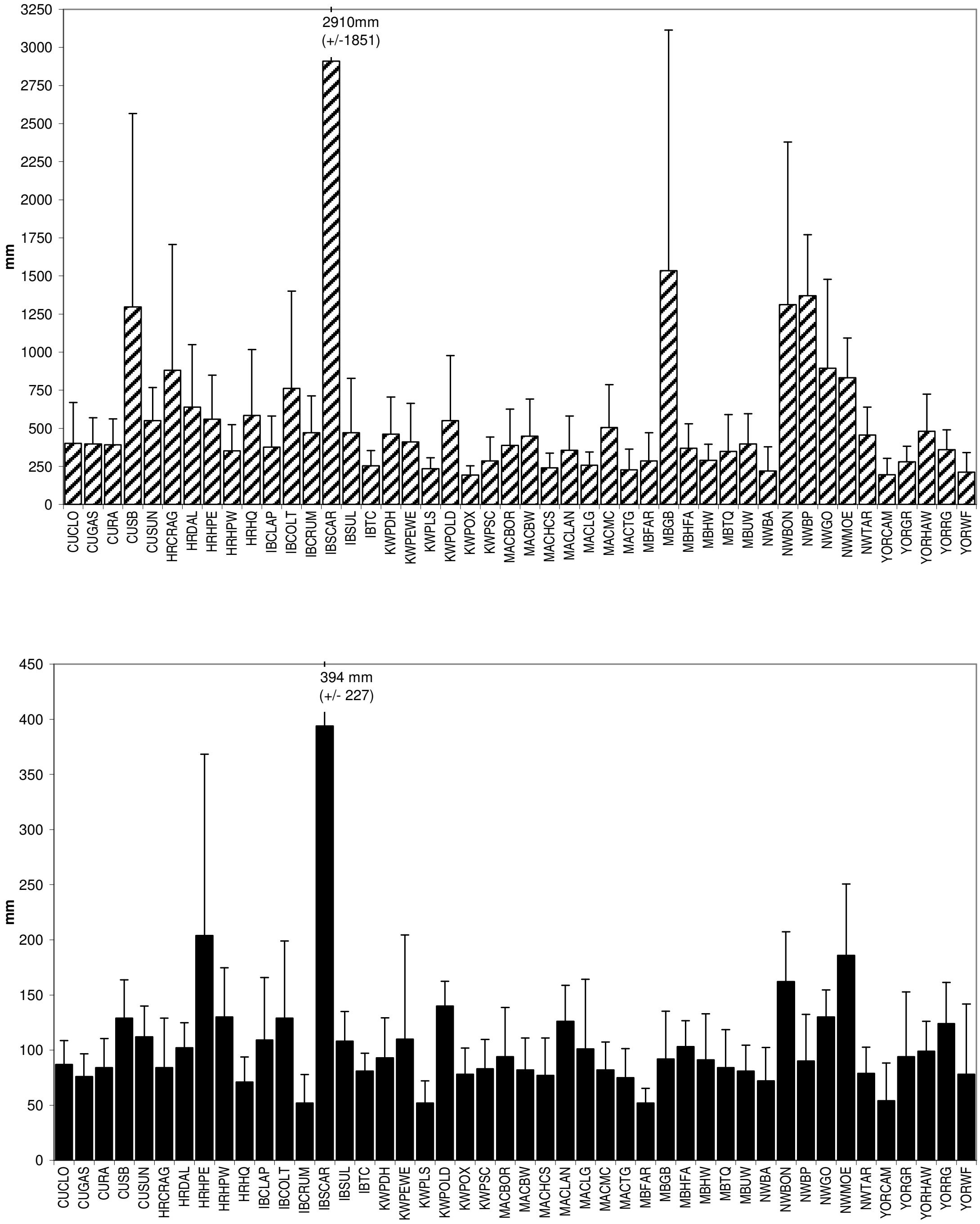

Figure 3-22: Mean runnel length (above) and width (below) at each limestone pavement with standard deviation indicated by positive error bars.

Runnel metrics are summarised in Figure 3-22 and Figure 3-23. With the exception of runnel frequency, runnel measurement showed a non-normal distribution (Kolmogorov-Smirnov test, p<0.05) and so data were transformed using square root transformations for runnel width and length data, as variance and mean were approximately equal (Field, 2005). Data then conformed to a normal distribution (Kolmogorov-Smirnov test, p>0.05).

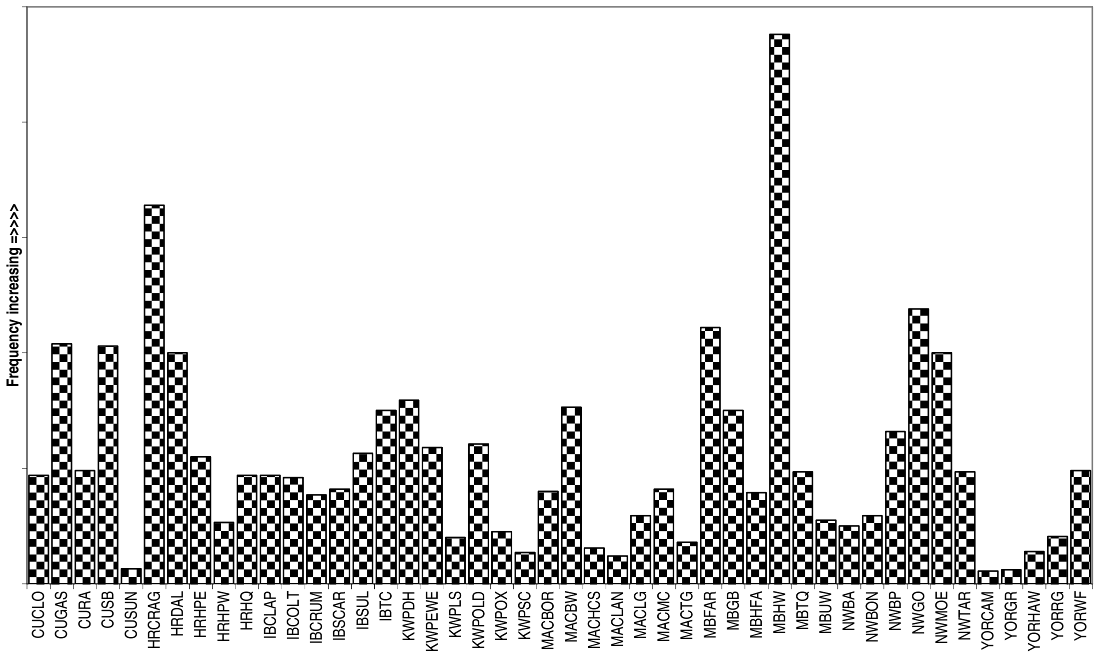

Figure 3-23: Frequency of runnels on each limestone pavement, with the higher bars indicating the greatest frequency of runnelling.

Table 3-10: Two-tailed Pearson correlation of runnel metrics against significant grike and clint metrics where ** indicates significance at the 0.01 level and * indicates significance at the 0.05 level (n=46).

	Grike depth	Runnel frequency	Clint width	Clint length	Clint perimeter	Runnel width	Runnel length
Runnel frequency	0.193	1	0.267	.306*	.332*	0.021	0.218
Runnel width	.337*	0.021	.613**	.594**	.555**	1	.686**
Runnel length	.560**	0.218	.714**	.663**	.645**	.686**	1

Pearson's correlation of runnel metrics with other geodiversity variables demonstrated a highly statistically significant relationship between runnel length and both clint size (width, length and perimeter) and grike depth. Similarly, runnel width shared a highly statistically significant positive relationship with clint metrics and had a significant positive relationship with grike depth (Table 3-10). The frequency of runnels on limestone pavement also showed a statistically significant positive relationship with limestone pavement dip ($r=0.36$, $p<0.05$, $n=46$), but goodness of fit was low with an R^2 value of just 0.13.

3.5.6 Limestone Pavement Geomorphological Features

Limestone pavement slope was measured at each site and was largely synonymous with pavement dip (see Section 3.2.3), but with notable exceptions. These include Trowbarrow (MBTQ), a vertical limestone pavement where bedding has tectonically displaced by around 90 degrees.
In line with the limestone pavement geomorphological features checklist, (see Appendix F) each pavement was assessed, and the number of features including solution pans, runnels etc. were noted. This measure was not an assessment of the quality of the limestone pavement geomorphology; it purely indicated the variety and type of features present. Analysis showed no significant difference between number of geomorphological features between the 46 limestone pavement sites (K-Wallis, $p>0.05$).

3.5.7 Human Influence on Limestone Pavement Geodiversity - Pavement Formation Assessment

Human influence on geodiversity of limestone pavements in the form of damage and physical removal of stone was recorded using the Pavement Formation Assessment (PFA) (Appendix H). The PFA offered a useful new method of assessing the intactness of the limestone pavement geodiversity (G. Ellis, 2007). It became available part way through this research so was used to assess during later field visits. It was also trialled on some previously visited pavements using the detailed ground photography that had been taken by the author during the research. In a small number of cases photographic assessment was made initially then a further site visit was conducted and a second PFA carried out. Results are summarised in Table 3-11.
The PFA offers a baseline monitoring tool recording the Extent (E) i.e. the percentage of the total area which is exposed rock, including both bedrock and rock fragments; and Condition (C) i.e. the percentage of that exposed rock that is broken fragments, excluding loose rock that is still clearly *in situ*. However, it does not include an assessment of the quality of the

geomorphology at the site. This aspect was therefore added to the monitoring tool and is presented alongside the PFA in Table 3-11.

Table 3-11: Assessment of intactness and quality of limestone pavements using the PFA monitoring tool along with a five-point geomorphology quality rating where five is the highest quality. PFA scores in red were recorded on site, whilst those in green were assessed from ground photographs.

Site	PFA Extent (E)	PFA Condition (C)	Geomorph quality	Site	PFA Extent (E)	PFA Condition (C)	Geomorph quality
CUCLO	E1	C1	5	MACBW	E1	C1	3
CUGAS	E2	C3	3	MACHCS	E1	C3	5
CURA	E1	C3	2	MACLAN	E2	C1	3
CUSB	E1	C3	5 in parts	MACLG	E2	C2	4
CUSUN	E2	C2	3	MACMC	E1	C1	5+
HRCRAG	E1	C1	5	MACTG	E2	C3	4
HRDAL	E2	C2	5 in parts	MBFAR	E1	C2	5 in parts
HRHPE	E1	C2	5	MBGB	E1/E1	C1/C1	5
HRHPW	E2	C2	4	MBHFA	E2	C2	3
HRHQ	E1	C1	5	MBHW	E1	C1	3
IBCLAP	E2	C4	1	MBTQ	E2	C1	3
IBCOLT	E1	C1	5	MBUW	E1	C1	4
IBCRUM	E2	C3	1	NWBA	E1	C3	4 in parts
IBSCAR	E1	C1	5	NWBON	E1	C1	1
IBSUL	E1	C1	5	NWBP	E1/E1	C1/C1	5
IBTC	E1	C1	5	NWGO	E1/E1	C1/C1	5
KWPDH	E1	C1	5	NWMOE	E2	C1	5
KWPEWE	E1	C2	3	NWTAR	E2	C1	3
KWPLS	E3	C3	2	YORCAM	E3	C1	3
KWPOLD	E1	C2	2	YORGR	E3	C2	3
KWPOX	E1	C2	5 in parts	YORHAW	E2	C3	3
KWPSC	E3	C3	3	YORRG	E2	C1	3
MACBOR	E1/E1	C1/C1	5 in parts	YORWF	E3	C3	1

The assessment of the geomorphological quality of the limestone pavement was a subjective view of the site, conducted by the author. It was a 'landscape scale' rating based on the presence of classic limestone pavement geomorphological features including distinct clints and grikes, solution runnels and solution pans (see Appendix F for geomorphology checklist).

3.6 Line Intercept Sampling

Line Intercept Sampling (LIS) offered a detailed and comparable 'window' across ten metres at the centre of the limestone pavement. Figure 3-24 presents the results from LIS measurements at 44 pavements, denoting the nature of the substrate type. It divided the pavement into grike, clint and 'other solution features' which included runnels and solution pans.

Multivariate analysis of the relationship between the differences in substrate type on each pavement showed no statistically significant relationships between the sites.

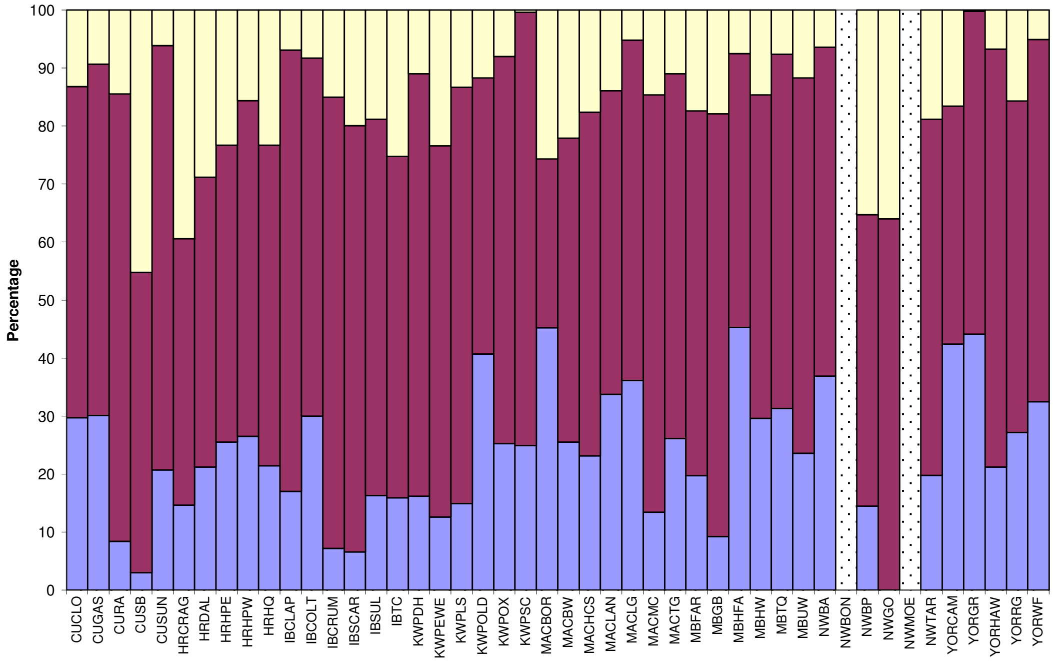

Figure 3-24: Substrate type across the 10m LIS, grike%=blue; clint and rubble %=purple; and solution features% (including runnels and solution pans)=beige. There was no LIS conducted at NWBON or NWMOE.

3.7 Pedology

Figure 3-25: Variation in soil profile at Holmepark Fell (HRHPE).

Soils taken from within the grikes were found to be quite variable, in all their properties, and this is summarised in Table 3-12. On some limestone pavements variability could be seen in the soil profile, as illustrated in Figure 3-25. The methodology that was employed sampled the deepest point of the auger only, and therefore did not record from each soil horizon in the profile.

Table 3-12: Properties of the soils taken by auger from within the grikes on the limestone pavements. * denotes missing value.

Site	Mean soil depth (mm)	Soil depth (sd)	Modal pH	Vari-ance pH	soil texture	Hue/Value/Chroma	Soil colour
CUCLO	196.7	5.03	7.5	0.25	sandy clay loam	2.5Y2.5/1	black
CUGAS	243.3	7.23	7.5	0.5	silty clay loam	7.5YR4/4	brown
CURA	123.3	7.37	7.5	0.5	silty loam	7.5YR4/2	brown
CUSB	260	10.58	7.5	0.25	silty loam	2.5Y2.51	black
CUSUN	226.7	6.43	7.5	0.25	silty loam	5YR3/3	dark reddish brown
HRCRAG	240	18.25	7.5	0.5	silty loam	2.5YR2.5/1	black
HRDAL	126.7	2.31	7.5	0.5	clay loam	5YR3/3	dark reddish brown
HRHPE	170	4.00	7.5	0.5	silty loam	2.5Y4/1	dark gray
HRHPW	53.3	1.53	7.5	0.25	silty loam	5YR3/1	very dark gray
HRHQ	73.3	5.86	7.5	0.5	silty loam	5YR3/2	dark reddish brown
IBCLAP	63.3	1.15	7.5	0.25	silty loam	10YR3/1	very dark gray
IBCOLT	350	1.73	7	0.5	clay loam	7.5YR2.5/1	black
IBCRUM	133.3	2.31	7.5	0.25	silty clay loam	5YR2.5/1	black
IBSCAR	110	7.94	7.5	0.25	*	7.5YR2.5/1	black
IBSUL	210	10.54	7.5	0.25	silty loam	10YR2/1	black
IBTC	80	5.00	7	0.25	silty loam	10YR2/1	black
KWPDH	180	14.73	7	0.75	silty loam	10YR3/2	very dark grayish brown
KWPEWE	233.3	3.21	7.5	0.5	silty loam	2.5Y2.5/1	black
KWPLS	40	0.00	7	0.5	silty clay loam	2.5Y2.5/1	black
KWPOLD	453.3	2.31	7.5	0.5	silty loam	7.5YR2.5/1	black
KWPOX	133.3	5.69	7	0.75	silty loam	7.5YR3/1	very dark gray
KWPSC	200	7.21	7.5	0.25	silty clay loam	7.5YR4/3	brown
MACBOR	126.7	7.02	7.5	0.25	silty loam	5Y2.5/2	black
MACBW	260	6.93	6.5	0.5	clay loam	7.5YR2.5/1	black
MACHCS	73.3	4.93	7.5	0.25	silty loam	10YR2/1	black
MACLAN	226.7	11.02	7	0.5	sandy loam	7.5YR2.5/2	very dark brown
MACLG	160	7.81	7.5	0.5	loam	7.5YR3/2	dark brown
MACMC	176.7	12.50	6	0.5	*	2.5Y2.5/1	black
MACTG	206.7	3.06	7.5	0.5	*	7.5YR2.5/1	black
MBFAR	116.7	1.53	7	0.25	silty loam	7.5YR2.5/1	black
MBGB	133.3	2.52	7.5	0.5	silty loam	5YR2.5/1	black
MBHFA	123.3	7.51	7.5	0.25	silty loam	10YR2/1	black
MBHW	216.7	9.02	7.5	0.5	loam	5YR2.5/2	black
MBTQ	183.3	4.62	7.5	0.5	silty loam	10YR2/2	very dark brown
MBUW	140	5.29	7	0.75	silty loam	10YR2/1	black
NWBA	56.7	1.53	7.5	0.25	silty loam	7.5YR3/2	dark brown
NWBON	83.3	3.21	7	0.75	silty loam	7.5YR3/2	dark brown
NWBP	66.7	3.51	7.5	0.5	sandy loam	2.5YR2.5/2	very dusky red
NWGO	180	1.73	7	0.5	clay	2.5YR3/4	dark reddish brown
NWMOE	230	*	7.5	*	sandy loam	7.5YR3/4	dark brown
NWTAR	70	3.61	7.5	0.25	loamy sand	7.5YR2.5/1	black
YORCAM	193.3	5.86	7	0.5	silty loam	5YR2.5/2	dark reddish brown
YORGR	220	5.29	7.5	0.5	loam	10YR2/1	black
YORHAW	283.3	5.51	7.5	0.5	silty loam	10YR2/2	very dark brown
YORRG	345	15.42	7.5	0.5	sandy loam	5YR2.5/2	very dusky red
YORWF	250	5.57	7.5	0.5	silty clay loam	5YR2.5/1	black

Soils varied considerably in texture from loamy sand to clay with a pH between 7-7.5. Soil depths in grikes were highly statistically significantly deeper where grikes were wider (r=0.465, p<0.001, n=46). Soil depth had significant negative relationships with sward height (r=$^{-}$0.322, p<0.05, n=46) and emergent height (r=$^{-}$0.386, p<0.01, n=46). This suggests that increased levels of grazing (as indicated by lower sward height) may lead to additional organic material in the soils resulting in deeper mean soil depth. In general, limestone pavements with greater emergent species height, i.e. wooded sites, had the shallowest soils in the grikes.

3.8 Summary of Geodiversity Results

The analysis of geodiversity variables assessed on 46 limestone pavements across the North West of England and North Wales has been presented in this chapter, and a summary follows. The limestone pavements in the study group were all formed on Carboniferous limestones but had two different lithologies, which markedly influenced their structure, due to changes in the depositional environment during formation. These were the Carboniferous Limestone Supergroup and the Yoredale Group.

Limestone pavement structure and form was also found to be influenced by proximity to a major fault. Pavements closer to a fault were significantly more likely to have a dip greater than 10° and smaller clint size. Additionally they displayed an increased frequency in jointing and higher levels of mineralisation.

Altitude had a highly significant relationship with a number of geodiversity variables. Limestone pavements at a higher elevation had significantly more extreme weather conditions with greater precipitation, windspeed and days frost. Geomorphologically, higher pavements had statistically shallower grikes and smaller clints, with fewer runnels. At the other end of the scale, a maritime influence on the limestone pavement significantly lowered precipitation and frost levels.

Shallow, wide grikes were found to be particularly associated with the Yoredale Group of limestone pavements. Deeper grikes had a significant relationship with larger clints while runnels were more frequent on longer clints and those with larger perimeter measurements. Runnels were longer and wider on larger clints and where the grikes were deeper.

A new tool for monitoring human influence on limestone pavement geodiversity, the Pavement Formation Assessment, was trialled during this research, and the results of piloting its use are presented in this chapter.

Soils sampled from grikes on the limestone pavements showed considerable variability, sometimes even within a single sample.

These results offer a detailed analysis of the geodiversity of limestone pavements. Along with results from the examination of biodiversity variables in the next chapter, they form a valuable framework to inform the holistic classification of limestone pavements.

4 ANALYSIS OF LIMESTONE PAVEMENT BIODIVERSITY

4.1 Introduction

Limestone pavements are generally rich sites for their biodiversity, both floral and faunal. Niche habitats are available for species to thrive at altitudes and exposures where they would normally perish (Silvertown, 1982; Ward & Evans, 1975). Silvertown (1982) and Webb and Glading (1998) argue that the woodland flora found in grikes on un-wooded pavements is "relic", in that it remains protected in the grikes from a time when the whole of the pavement site was wooded during the Iron Age (Chapman, 2007; Silvertown, 1982).

The aim of this work was to examine the relationship between geodiversity and biodiversity on limestone pavements in order to gain a fuller understanding of the key influences that determine the different types of limestone pavement observed. This would then form the basis for the holistic classification of limestone pavement.

The approach throughout this research was to build on techniques that have been developed by experts in the field, and Ward and Evans' (1975) seminal study, on behalf of the Institute of Terrestrial Ecology, provided a backbone for the methods used to evaluate limestone pavement biodiversity. However, it was felt important to include not only the deep grike flora that Ward and Evans examined (Ward & Evans, 1975), but also shallower grike flora, in order to get the fullest picture of the plant communities present at each site. This is because the research aimed to assess a full range of randomly selected limestone pavements which were likely to include pavements with deep grikes, shallower grikes, areas of broken pavement and wooded stands. Thus plant data incorporated any plant species found within any grike within the delineated area of the limestone pavement.

Further to this, bryophyte species were included in this investigation as mosses can act as indicator species, being a valuable addition to the classification. Examining lichens on the limestone pavements, a factor that was noted as an element missing from Ward and Evans (1975) work, was considered. However, as this is an exceptionally difficult taxonomic group to identify, with 923 taxa in Yorkshire alone (Seaward, 2008), it was considered beyond the scope of this research.

A full outline of the approach and methods used to collect data for the measurement of limestone pavement biodiversity was discussed in Chapter 2. This chapter describes the results of the analysis of the biodiversity data collected according to these methodologies.

4.2 Floral Species Richness

Species richness is simply the number of floral species in each sample unit, in this case on each limestone pavement. Species richness is one element of conservation value but it does not offer information on the quality of the floral community. Also, species richness on its own does not distinguish between native and non-native species or rarity (Fleishman *et al.*, 2006). However species richness does provide a quantitative baseline measurement which, added to qualitative data such as size, diversity, naturalness, rarity, fragility and typical-ness, offers a picture of the floral communities site by site.

4.2.1 Species Area Curves

Evaluation of species richness by pavement area is examined in Figure 4-1 displaying the relationship between total numbers of species recorded and the size of the limestone pavement that was examined. Limestone pavement does not necessarily follow the classic rules of an increase in plot size offering proportionally more floral habitat. This is because floral habitat availability is more closely related to the extent of the site that is covered in un-fractured rock and with geomorphological factors, as was discussed in Chapter 3.

Limestone pavement area data did not conform to a normal distribution (Kolmogorov-Smirnov test, $p<0.05$), demonstrating a positive skew, so square root transformations were conducted (Field, 2005). This then produced a normal distribution curve (Kolmogorov-Smirnov test, $p>0.05$). Correlation of the transformed limestone pavement area data with the normally distributed species richness data showed a highly statistically significant positive relationship (r=0.38, p<0.01, n=46). Calculating the goodness of fit indicated that 14% of the rise in species richness was explained by increase in pavement size (R^2=0.14), suggesting that limestone pavement size is only one of a number of factors dictating the number of plant species present on limestone pavements; a finding in accordance with the work of Thom, Swain, Brandes, Burrows, Gill and Tupholme regarding the limestone pavements of the Yorkshire Dales National Park (Thom *et al.*, 2003).

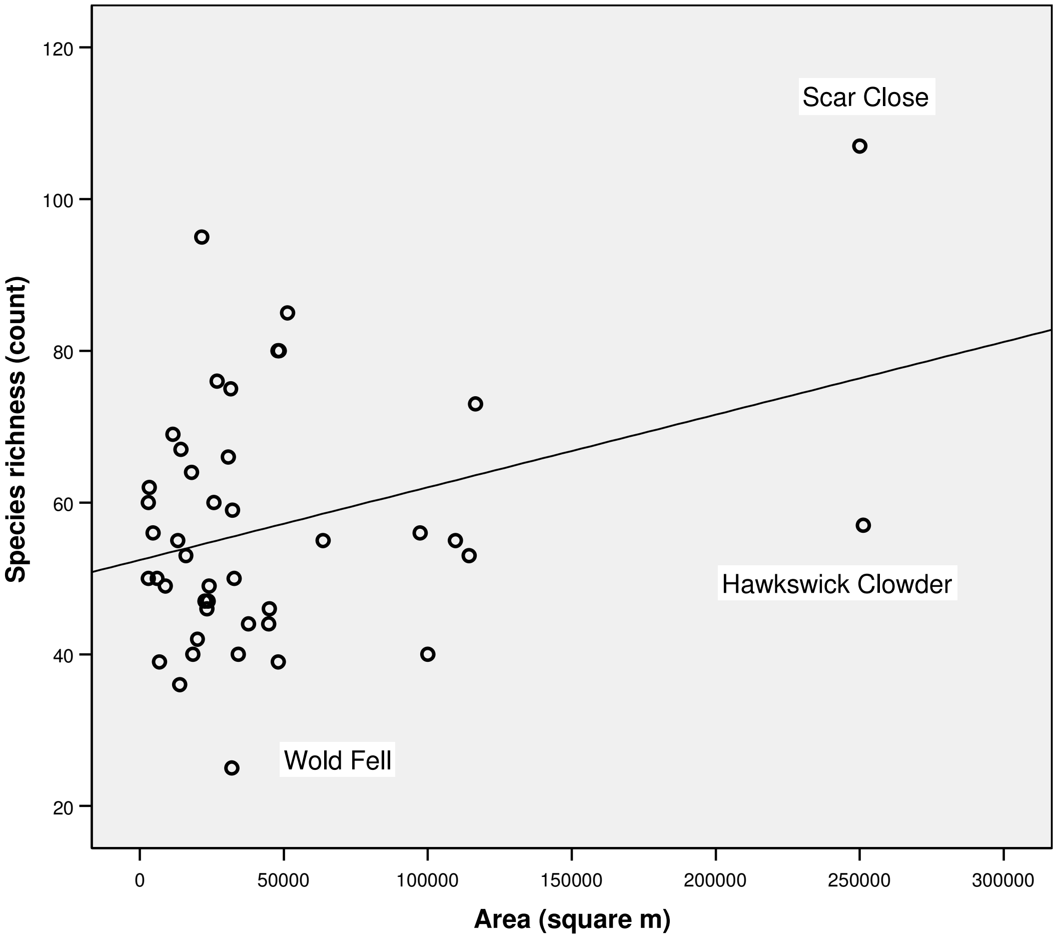

Figure 4-1: The relationship between pavement area and species richness i.e. the number of species on each limestone pavement, with line of best fit. Notable outliers are labelled with the pavement name.

4.2.2 Total Species Frequency

A total of 289 higher plant and bryophyte species were found in pavement grikes. Figure 4-2 illustrates the distribution of species richness (using presence/absence data) on the 46 pavements that were visited over the two years of fieldwork, giving an indication of the type of vegetation found on each pavement. Limestone pavements are presented in order of size from Hawkswick Clowder (YORHAW), the largest at 25,742 square metres (25.12ha), to Moelfre (NWMOE), the smallest at 240 square metres (0.024ha). The top four most species-rich limestone pavements were all in Yorkshire; Scar Close (IBSCAR), with 107 species; Top Cow (IBTC), 95 species; Tennant Gill (MACTG), 85 species; and Colt Park Wood (IBCOLT), having 82 species. The least species-rich limestone pavement was the very small coastal stand at Moelfre (NWMOE) on Anglesey with only 13 species located there. The most species-rich limestone pavement in North Wales was Bryn Pydew. This was the 14th richest limestone pavement visited with 62 species found on the 0.332ha limestone pavement area.

It should be noted that those pavements that were most species-rich were not necessarily the largest (for analysis of the relationship between pavement area and species count see Section 4.2.1). However the top ten have all had ongoing conservation management from their Country Agency (in most instances Natural England). All ten of the most species-rich are in England, with five of these within National Nature Reserves (NNRs), namely Scar Close, Top Cow, Colt Park, Holme Park Quarry (HRHQ) and Royalty Allotment (CURA). The other five species-rich limestone pavements in the top ten are protected within SSSIs, thus all have statutory protection. Bryn Pydew, the richest limestone pavement in North Wales, has protection as a Regionally Important Geodiversity Sites (RIGS) designation and is a Wildlife Trust Local Nature Reserve.

4.2.3 <u>Rare Pavement Species</u>

There is general agreement that the presence of rare species on limestone pavement indicates the conservation value of the pavement, as a number of species are dependent on limestone pavement for their survival (JNCC, 1997; Usher, 1980; Ward & Evans, 1975). Ward and Evans termed these species ‘A’ and ‘B’ species (Ward & Evans, 1975). ‘A’ species are those species which have a very high conservation value as they are rare and dependent on limestone pavement habitat for maintaining their populations in the UK.

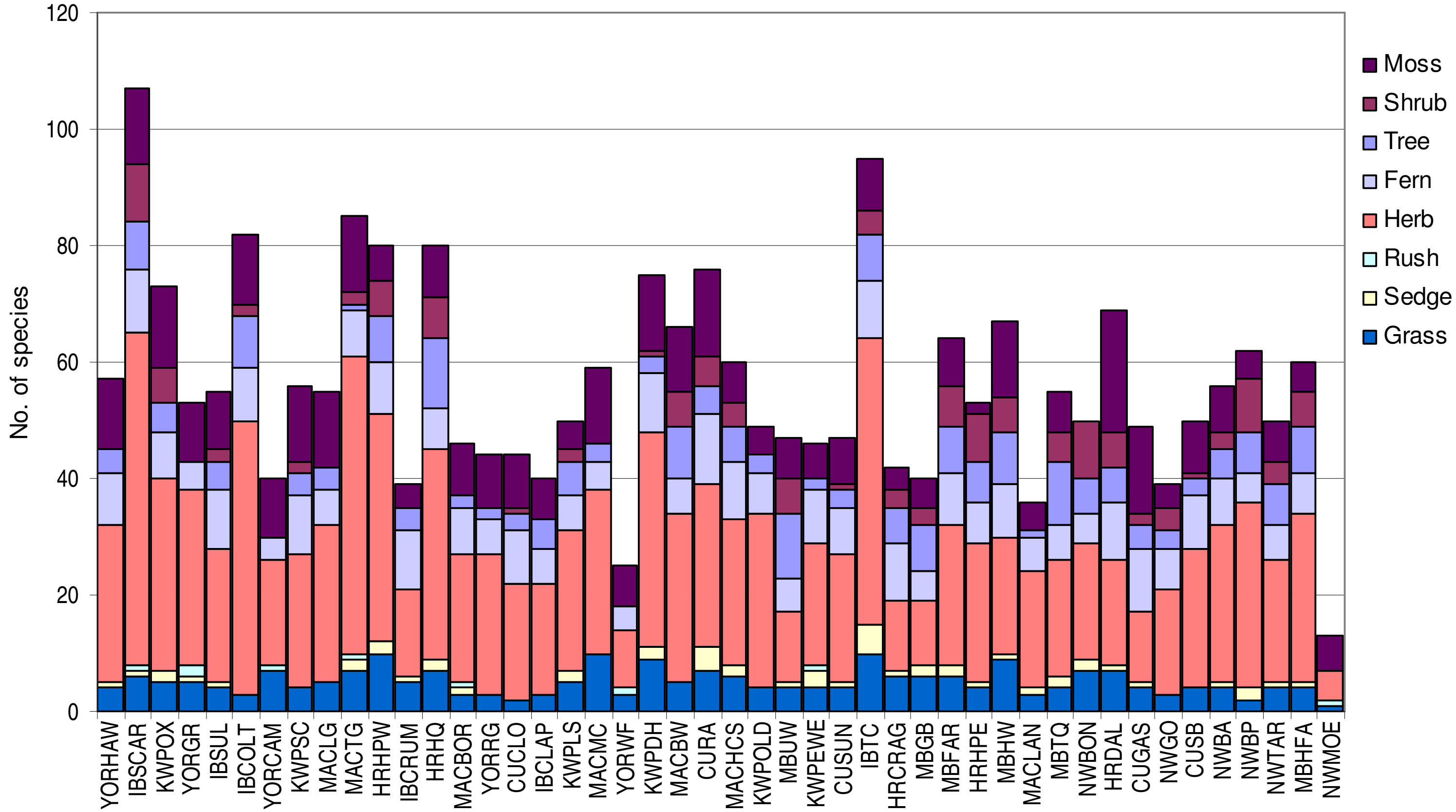

Figure 4-2: Higher and lower plant species present on each pavement stand, sub-divided by floral type, showing pavement species richness. Pavements ordered by size from largest to smallest, left to right.

Figure 4-3: *Actaea spicata* (Baneberry), a limestone pavement 'A' species.

Figure 4-4: *Epipactis atrorubens* (Dark red helleborine), a limestone pavement 'A' species.

Two examples are illustrated in Figure 4-3 and Figure 4-4. 'B' species are also dependent on pavement habitats, and may be regionally fairly widespread but are sparsely distributed over the country as a whole.

For the purposes of this research, the 'A' and 'B' species were used to denote highly favoured limestone pavement species that have important conservation value. To these were added some plant species presented by the JNCC as important limestone pavement species in their conservation management objectives (JNCC, 1997).

The frequency distribution of these rare species can be seen in Figure 4-5. There were only three 'A' species that were not found on any of the 46 pavements in the study group (*Carex digitata*, *Dryas octopetala* and *Salix myrsinites*), and four 'B' species. There was a statistically significant positive correlation between area and rare species ($r=0.299$, $p=0.044$, $n=46$). Investigating the hypothesis that the number of species with a high conservation value on limestone pavement are dependent on the size of the stand resulted in a very low R^2 value of 0.09. This suggests that although the relationship between pavement area and number of rare species was statistically significant it only explains a very small part of the overall complexity relating to the biodiversity of limestone pavements.

Table 4-1: A list of species which depend on limestone pavement habitats for their continued survival.

Latin Name	English Name	Importance
Actaea spicata	Baneberry	'A' species
Carex digitata	Fingered sedge	'A' species
Dryas octopetala	Mountain avens	'A' species
Dryopteris submontana	Rigid buckler-fern	'A' species
Epipactis atrorubens	Dark-red helleborine	'A' species
Gymnocarpium robertianum	Limestone fern	'A' species
Hypericum montanum	Pale St John's-wort	'A' species
Polygonatum odoratum	Angular Solomon's seal	'A' species
Ribes spicatum	Downy currant	'A' species
Salix myrsinites	Myrtle-leaved willow (Scotland)	'A' species
Arabis hirsute	Hairy rock cress	'B' species
Arum maculatum	Lords and ladies	'B' species
Asplenium viride	Green spleenwort	'B' species
Cardamine impatiens	Narrow-leaved bittercress	'B' species
Centaurium erythraea	Common centaury	'B' species
Ceterach officinarum	Rusty back fern	'B' species
Circaea lutetiana	Enchanter's nightshade	'B' species
Cirsium heterophyllum	Melancholy thistle	'B' species
Clematis vitalba	Clematis	'B' species
Cochlearia officinalis	Scurvy-grass	'B' species
Convallaria majalis	Lily-of-the-valley	'B' species
Crepis paludosa	Marsh hawk's-beard	'B' species
Cystopteris fragilis	Brittle bladder-fern	'B' species
Eupatorium cannabinum	Hemp-agrimony	'B' species
Galium boreale	Northern bedstraw	'B' species
Geranium lucidum	Shining crane's-bill	'B' species
Geranium sanguineum	Bloody crane's-bill	'B' species
Geranium sylvaticum	Wood crane's-bill	'B' species
Inula conyzae	Ploughman's-spikenard	'B' species
Juniper communis	Juniper	'B' species
Melica nutans	Mountain melick	'B' species
Melica uniflora	Wood melick	'B' species
Mycelis muralis	Wall lettuce	'B' species
Myosotis sylvatica	Wood forget-me-not	'B' species
Paris quadrifolia	Herb paris	'B' species
Polystichum aculeatum	Hard shield-fern	'B' species
Polystichum lonchitis	Holly fern	'B' species
Potentilla crantzii	Alpine cinquefoil	'B' species
Prunus padus	Bird cherry	'B' species
Rhamnus cathartica	Common buckthorn	'B' species
Rosa pimpinellifolia	Burnet rose	'B' species
Rubus saxatilis	Stone bramble	'B' species
Saxifraga hypnoides	Mossy saxifrage	'B' species
Taxus baccata	Yew	'B' species
Thalictrum minus	Lesser meadow-rue	'B' species
Trollius europaeus	Globeflower	'B' species
Viola hirta	Hairy violet	'B' species

It was notable that some of the smaller pavements, including Farrar's Allotment (MBFAR) and Holme Park East (HRHPE), had as many rare ('A' and 'B') limestone pavement species as pavements three times their size. Relationships between rarity and grike metrics are considered in the next section, whilst the effects of different grazing intensities on rare species presence are examined in Section 4.4.2.

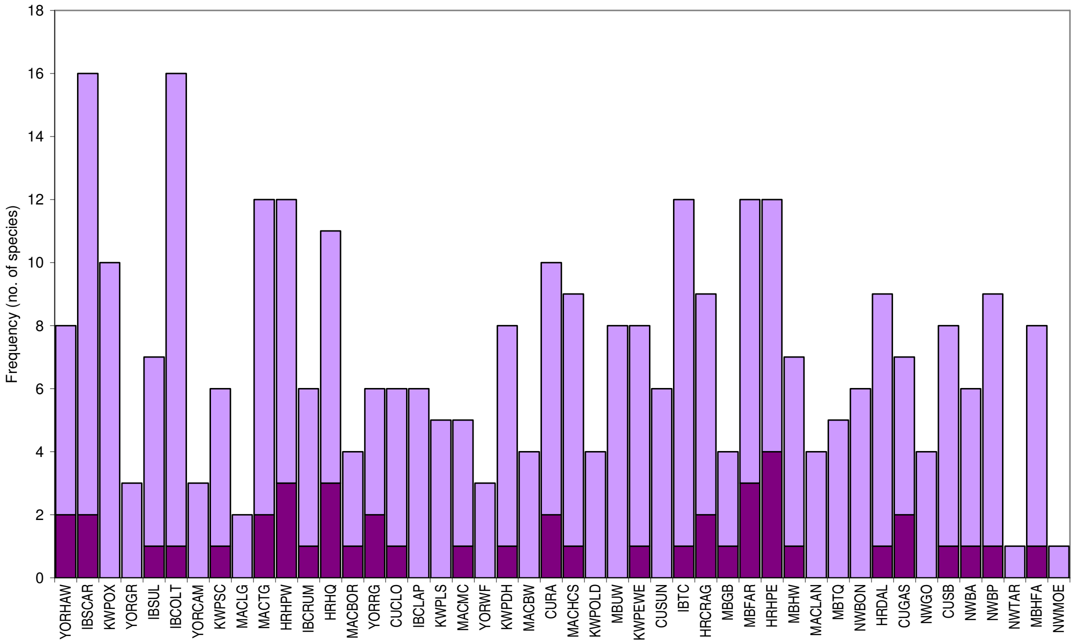

Figure 4-5: Frequency of rare species on each pavement stand. Lower section of each column represents the rarer 'A' species, whilst the upper section shows 'B' species which are still dependent on limestone pavement for their survival. Pavement stands are again in order of size with the largest to the left.

4.2.4 <u>The Relationship between Grike Metrics and Plant Species Richness</u>

Previous research suggests that deeper grikes are associated with a higher presence of limestone pavement specialist species (Silvertown, 1983; Ward & Evans, 1976). This hypothesis was therefore considered by correlating grike depth and grike width with plant community data, using Spearman rank correlation, as some data were not normally distributed. The results are presented in Table 4-2 and it indicates that there was a highly statistically significant positive relationship between grike depth and the presence of rare ('A' and 'B') species on the limestone pavements (r_s=0.449, p<0.01, n=46). A highly statistically significant positive relationship is also seen between species richness and presence of limestone pavement specialist species (r_s=0.686, p<0.01, n=46).

Table 4-2: Spearman rank correlation of grike metrics with plant species presence on the 46 limestone pavements where ** indicates significance at the 0.01 level, n=46.

		Grike depth (mean)	Grike width (mean)	Species richness	AB species
Grike depth (mean)	Correlation Coefficient	1.000	-.265	.164	.449**
Grike width (mean)	Correlation Coefficient	-.265	1.000	-.193	-.199
Species richness	Correlation Coefficient	.164	-.193	1.000	.686**
AB species	Correlation Coefficient	.449**	-.199	.686**	1.000

There was no significant relationship demonstrated between grike metrics and species richness and the negative relationship between grike width and species richness and AB species presence was not significant. Examination of the goodness of fit of this relationship indicated that 22% of the variation in numbers of limestone specialist species was explained by the depth of the grikes.

4.2.5 <u>Less Favoured Limestone Pavement Species</u>

In considering favourable conservation management, the species composition is very important, and particularly the presence/absence of what are considered 'negative' species (JNCC, 1997; Thom *et al.*, 2003). There were two main types of 'negative' species found on limestone pavements, as illustrated in Figure 4-6.

'Negative 1' species are classic farm ruderals, indicative of intensive farming, and include *Cirsium arvense* (Creeping thistle) and *Cirsium vulgare* (Spear thistle). Both of these prefer disturbed conditions and are robust and unpalatable to grazing stock (Brandes, 2000). *Urtica dioica* (Nettle), *Rumex obtusifolius* (Broad-leaved dock) and *Senecio jacobaea* (Ragwort) thrive in nutrient-rich conditions and set seed in the bare ground produced by rabbit or sheep grazing (Averis *et al.*, 2004). Together these species tend to provide evidence of "unsustainable management within a farming system" (JNCC, 1997) and suggest sub-optimal management of an area (S. Webb, 12th January 2009, pers. comm.).

That said, there are examples of negative 1 species occurring on limestone pavements such as Scar Close (IBSCAR), a species-rich, thriving pavement which hosts thirteen rare limestone pavement species; so the presence here of these ruderals is somewhat incidental. It is important, therefore, to consider these indicators in context (T. Thom, S. Ward and S. Webb, 16th January 2009, pers. comm.).

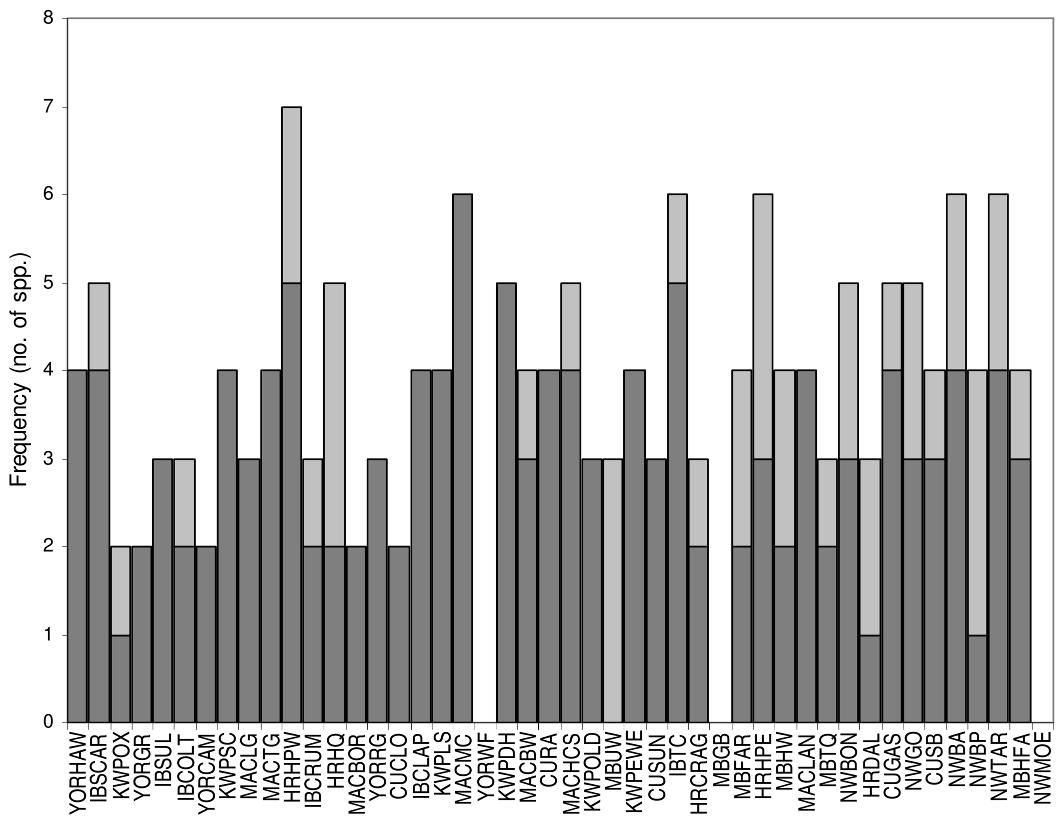

Figure 4-6: Breakdown of 'negative indicator species' on limestone pavement. Lower sections of columns are species that indicate unsustainable farm management and include Thistle, Nettle and Dock, whereas upper sections of columns are species that have a negative impact on the overall biodiversity of limestone pavement. Pavement stands are in order of size with the largest to the left.

'Negative 2' species are those species that have a negative impact on other more highly valued limestone pavement species. They include the invasive Cotoneaster (Figure 4-7), as the fast-growing, prostrate spreading habit of this plant shades out more tender species, potentially reducing pavement diversity (Bond, 2003). Species with prolific and/or waxy leaf fall can have a similar negative effect on biodiversity. These include *Ulex europaeus* (Gorse), *Fagus sylvatica* (Beech) and *Thuja plicata* (Western red cedar), species which rarely occur in equilibrium with other species (S. Webb, 12th January 2009, pers. comm.). *Centranthus ruber* (Red valerian) and *Pteridium aquilinum* (Bracken) are considered negative as they are highly competitive, and once established they suppress and out-compete other species. With the predicted changes to our climate these may potentially pose an even bigger problem in the future (T. Thom, S. Ward and S. Webb, 16th January 2009, pers. comm.).

Figure 4-7: *Cotoneaster integrifolius* (small-leaved Cotoneaster), a garden escapee. Its berries are spread prolifically by birds, leading to rapid colonisation of limestone pavements, particularly those at lower altitudes such as the Morecambe Bay pavements and those in North Wales. It is also particularly resistant to management strategies so poses a significant problem to pavement diversity (Bond, 2003).

There is an on-going debate about the value of Sycamore, *Acer pseudoplatanus*, both generally (Harris, 1987) and especially on limestone pavements where it has historically been mechanically or chemically removed from a number of sites (pers. obs.). Its habit of leafing early in the year causes shading and its high volume of leaf litter and seeding may smother some grike species, but on pavements it can also be a stable, classic landscape feature, sculptured over time. When it is in equilibrium Sycamore can provide a similar structure and cover to that offered by ash, and it has particular added value as a host for invertebrates and lichens (S. Ward, 15th January 2009, pers. comm.). For these reasons it was not included within the categories of 'negative species', though it is noted that condition assessment of English limestone pavements dictates that there should be no more than 10% sycamore/blackthorn combined of the woody element of the limestone pavement in order to achieve favourable condition (JNCC, 1998).

Correlation between less favoured species and limestone pavement size was investigated using SPSS (SPSS for Windows, 2005) using square root transformed area data to conform to test assumptions. The relationship between 'negative 1' species (normally distributed data) and area was not statistically significant. 'Negative 2' species data were not normally distributed so non-parametric correlation was used to examine the relationship with area. There was a highly statistically significant negative relationship between negative 2 species and the size of the limestone pavement (Spearman Rank, $r_s = {}^{-}0.43$, $p<0.01$, $n=46$).

4.2.6 Human Influence and Limestone Pavement Flora

Human influence on the limestone pavement flora was estimated during fieldwork by recording the ease of access to the site on a four point scale (where difficult access=1; low accessibility=2; medium accessibility=3 and very accessible=4). The volume of litter at each site was also counted and contributed to this assessment. Additionally, the degree of footfall/trampling on the limestone pavement was recorded (where none=0; light=1; medium=2 and heavy=3). No statistically significant relationship was identified when either of these measures was correlated against plant species richness, rare plant species presence, or 'negative 1' species occurrence.

Visitor impact was seen by the amount of litter that was present at each limestone pavement. There was a highly significant relationship identified between amount of footfall/trampling and the number of pieces of litter found at the site (Spearman Rank, $r_s=0.39$, $p<0.01$, $n=46$) with an R^2 value of 0.225 suggesting that 22.5% of the variation in the amount of litter is explained by the volume of visitors at each limestone pavement.

4.3 Biodiversity and Altitude

The relationship between altitude and plant species was examined by multivariate analysis, using a statistical package specifically designed to analyse ecological communities with large datasets and independent variables. PC-ORD (McCune & Mefford, 2006) calculated a distance matrix measuring similarities between the 46 pavement stands, based on the patterns of shared abundances of the species present. This was then used as the basis of subsequent analyses.

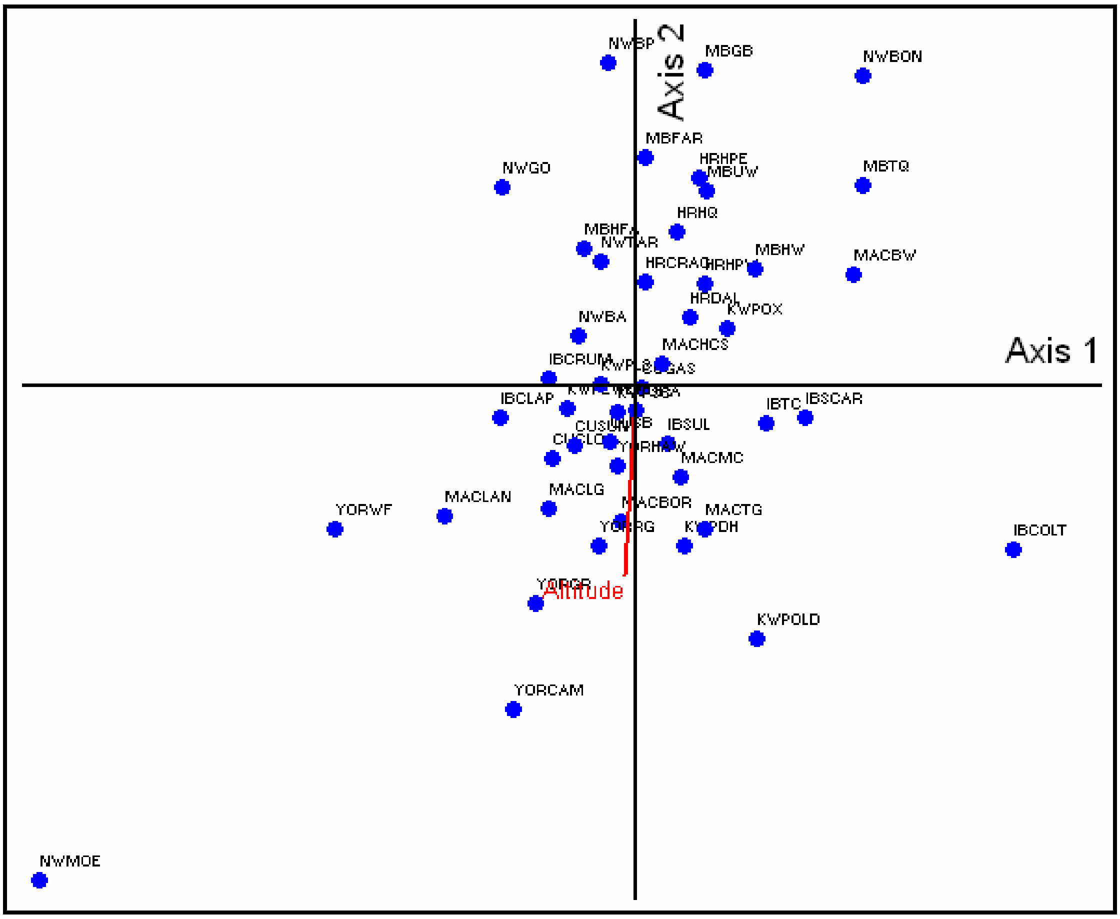

Figure 4-8: Ordination of similarity between stands based on total species composition using NMS. Vector (red) indicates direction and strength of subsequent bivariate correlation of axis scores with the environmental variable altitude.

PC-ORD allows the most appropriate distance measure to be chosen, and the Sørensen distance measure was used, which calculated distance on the basis of proportion of abundance that was shared among species. This works well for community species data where there are many zeros and outliers present (Kent, 2006; McCune & Grace, 2002). Nonmetric Multidimensional Scaling

(NMS) was then used to ordinate the species matrix with environmental data to extract underlying gradients, in this instance the relationship between the plant species and the altitude of the limestone pavement.

Figure 4-8 displays the NMS ordination generated using untransformed species abundance data with a random starting configuration. A Monte Carlo test indicated a two-dimensional solution, after 500 iterations, which resulted in a final stress score of 14.95, p=0.0001 indicating a reasonable fit (Clarke, 1993; Kruskal, 1964). Post hoc assessment of the quality of the data reduction by ordination indicated that less than 1% of the original variation was represented by axis 1 (R^2=0.002) and 34% by axis 2 (R^2=0.343) with a cumulative 35% of the original variation represented.

Table 4-3: Negative Pearson correlation coefficient scores (r) between ordination axis 2 (Figure 4-8) and altitude, i.e. indicative of plant species that have a significant relationship with higher altitudes. The critical value for r is 0.288 at p<0.05 (* indicates significance) and is 0.372 at p<0.01 (indicates significance) (n=46, df=45) (Fowler *et al.*, 2002).**

Plant species	Common name	AXIS 2 r value	AXIS 2 r-sq
Rhytidiadelphus squarrosus	Moss	¯0.546**	0.298
Asplenium viride	Green spleenwort ('B' species)	¯0.486**	0.236
Urtica dioica	Nettle	¯0.467**	0.218
Cirsium vulgare	Spear thistle	¯0.433**	0.188
Luzula campestris	Field woodrush	¯0.394**	0.155
Cystopteris fragilis	Brittle bladder-fern ('B' species)	¯0.389**	0.152
Homalothecium spp.	Moss	¯0.385**	0.148
Cardamine pratensis	Cuckoo flower	¯0.381**	0.145
Achillea millefolium	Yarrow	¯0.372**	0.138
Climacium dendroides	Moss	¯0.372**	0.139
Trifolium spp.	Clover	¯0.348*	0.121
Galium sterneri	Limestone bedstraw	¯0.314*	0.099
Cirsium palustre	Marsh thistle	¯0.313*	0.098
Conocephalum spp.	Liverwort	¯0.311*	0.097
Oxalis acetosella	Wood-sorrel	¯0.301*	0.09
Rhytidiadelphus triquetrus	Moss	¯0.296*	0.087
Festuca rubra	Red fescue	¯0.292*	0.085

The multivariate analysis clustered the limestone pavements in ordination space according to their plant communities. Subsequent bivariate correlation with axes scores specified that altitude had a significant relationship with the gradient of the ordination, indicated using a red vector (Figure 4-8).

Altitude is the red vector in Figure 4-8 and it correlated very strongly with axis 2 (r=¯0.617, p<0.01) demonstrating the influence that altitude has on limestone pavement plant communities. The relationship between altitude and individual plant species was then considered by examining the correlation scores for altitude and ordination axis 2. Plant species that demonstrated significant relationships with altitude are presented in Table 4-3 and Table 4-4. Species which occurred on less than 5% of the limestone pavement stands were eliminated in order to reduce the likelihood of spurious relationships and to enhance the detection of relationships between plant community composition and environmental factors (McCune & Grace, 2002).

By inference, statistically significant negative correlation scores between axis 2 and plant species signify species that are associated with higher altitude limestone pavements (Table 4-3). *Asplenium viride* (Green spleenwort) is an example of a species known to be associated with upland limestone areas (Merryweather & Hill, 1992) and this relationship is demonstrated in Table 4-3, where the coefficient score is highly significant ($r = {}^{-}0.486$, $p < 0.01$).

Conversely, plants that positively correlate with axis 2 (Table 4-4) indicate species that show a negative association with higher altitudes, i.e. they have a statistically significant positive relationship with lower altitude limestone pavements. In Table 4-4 species are presented in order of the strength of the correlation, signifying the degree of influence that altitude has on specific plants on limestone pavements. Plants that have a high conservation value on limestone pavements (‘B’ species - see Section 4.2.3) are indicated accordingly.

The relationship between limestone pavement plant communities and other environmental variables is expanded in Chapter 5, as part of the holistic classification of limestone pavements.

Table 4-4 (over page): Positive Pearson correlation coefficient scores (r) between ordination axis 2 (Figure 4-8) and altitude, i.e. indicative of plant species that have a significant relationship with lower altitudes. The critical value for r is 0.288 at $p < 0.05$ (* indicates significance) and is 0.372 at $p < 0.01$ (indicates significance) (n=46, df=45) (Fowler *et al.*, 2002).**

Plant species	Abbreviated name	AXIS 2	
		r value	r-sq
Brachypodium sylvaticum	False brome	0.702**	0.492
Rosa canina	Dog-rose	0.7**	0.489
Hedera helix	Ivy	0.693**	0.481
Teucrium scorodonia	Wood sage	0.674**	0.454
Prunus spinosa	Blackthorn	0.652**	0.425
Crataegus monogyna	Hawthorn	0.637**	0.406
Taxus baccata	Yew ('B' species)	0.618**	0.382
Ilex aquifolium	Holly	0.573**	0.328
Acer pseudoplatanus	Sycamore	0.571**	0.327
Fraxinus excelsior	Ash	0.539**	0.29
Pteridium aquilinum	Bracken	0.525**	0.276
Asplenium trichomanes	Maidenhair spleenwort	0.523**	0.274
Corylus avellana	Hazel	0.51**	0.26
Ligustrum vulgare	Wild privet	0.467**	0.218
Juniperus communis	Juniper ('B' species)	0.449**	0.202
Lonicera periclymenum	Honeysuckle	0.428**	0.183
Geranium robertianum	Herb Robert	0.405**	0.164
Solidago virgaurea	Goldenrod	0.402**	0.161
Phyllitis scolopendrium	Hart's-tongue fern	0.395**	0.156
Tamus communis	Black bryony	0.393**	0.154
Pilosella officinarum	Mouse-ear hawkweed	0.392**	0.154
Betula pendula	Silver birch	0.388**	0.151
Fragaria vesca	Wild strawberry	0.383**	0.146
Quercus spp.	Oak	0.381**	0.146
Ulex europaeus	Gorse	0.374**	0.14
Helianthemum nummularium	Common rock-rose	0.369*	0.136
Centaurea nigra	Knapweed	0.364*	0.132
Viola hirta	Hairy violet ('B' species)	0.357*	0.127
Geranium sanguinium	Bloody crane's-bill ('B' species)	0.353*	0.124
Cotoneaster spp.	Cotoneaster	0.351*	0.123
Pimpinella saxifraga	Burnet-saxifrage	0.344*	0.119
Sorbus aria	Common whitebeam	0.342*	0.117
Senecio jacobaea	Ragwort	0.339*	0.115
Erica cinerea	Bell heather	0.337*	0.114
Plantago lanceolata	Ribwort plantain	0.328*	0.108
Sorbus aucuparia	Rowan	0.327*	0.107
Inula conyzae	Ploughman's-spikenard ('B' species)	0.319*	0.102
Ulmus glabra	Wych elm	0.288*	0.083

4.4 Biodiversity and Grazing intensity

Grazing has been recognised as an important issue in relation to biodiversity on limestone pavements (Conway & Onslow, 1999; Dunford, 2001; Mercer & Evans, 1997; Thom *et al.*, 2003; Ward & Evans, 1976; Webb & Glading, 1998). Goldie (1976), quoting Pearsall (1934), said that "it is evident that quite intermittent grazing suffices to prevent regeneration of woodland". The impact of high grazing regimes is illustrated in Figure 4-9 and Figure 4-10 which depict dwarf growth patterns in trees subjected to high level grazing and Nettles, a less favoured limestone pavement species, associated with soil disturbance and eutrophication.

Figure 4-9: Evidence of the impact of grazing on limestone pavements, showing gnarled Hawthorn and scats at Smearsett Copys (left) with a Nettle filled 'rabbit-run' caused by soil enrichment from rabbit droppings in a grike at Bordley (right).

Ward and Evans (1978) outline key differences in land use between low altitude (30-80m) and high altitude limestone pavements (over 100m) in Cumbria. They state that generally pavements are considered to be un-productive but at higher altitudes the fullest use is made of all land and the barrenness of pavement compared to "adjacent low productivity grassland" is not so marked a difference and is therefore incorporated into "sheep-walks". Lower altitude pavement compares so unfavourably to adjacent land that it is more likely to be left as "secluded clearings within woodland or rough grazing with low stocking density" (Ward & Evans, 1978). This pattern is also seen widely across Yorkshire, which has a long history of high stocking densities associated with limestone pavement with subsequent loss of biodiversity (Thom *et al.*, 2003).

Mercer and Evans (1997) note that on Tennant Gill (MACTG), a small pavement in the YDNP, Lily of the valley and Globeflower were recorded by Ward and Evans in 1976, but despite repeat surveys in the 1980s and early 1990s the species were not re-recorded until 1996, when they were found in low numbers. The authors postulate that it has therefore taken four growing seasons without grazing and with reduced rabbit populations for these grazing intolerant species to either extend from relict rootstock or to re-establish from seed.

Figure 4-10: Dwarf Hawthorn on pavement outcrop at Little Stainforth, Yorkshire, illustrating the effects of grazing and restricted nutrient availability resulting in the classic stunted growth patterns seen in trees growing on limestone pavement.

Overgrazing is not the only issue affecting limestone pavement; under-grazing can also be detrimental to biodiversity, leading to scrub encroachment. Dunford (2001) researched the problem of under-grazing on the limestone pavements and grasslands of the Burren, in the Republic of Ireland, during the winter period which had led to dense scrub encroachment. He proposed that this was addressed by increased grazing, termed ‘conservation-grazing’. In certain instances where scrub encroachment has already taken place, grazing is recommended over the spring time until 1st June, as this is when scrub is most palatable. Although this may impact flowering it is hoped that, after the grazing ceases, a second crop of flowers will be produced. Dunford also cites other factors as being important to grazing impact. Along with species and breed these include grazer age, sex, background, temperament and "herd behaviour" (Dunford, 2001).

In Wales, Conway and Onslow (1999) correlated grazing (stocking rate) and biodiversity on the Welsh limestone pavements. Using the Ward and Evans' Floristic Index to assess the quality of the flora, they found a statistically significant negative correlation between sheep grazing intensity and floral quality, though investigation indicated that only 18% of the variation in floral quality was explained by this relationship (R^2=0.18). Sheep also have a preference for grazing limestone grassland areas (Armstrong *et al.*, 1997a, 1997b; Burek & Conway, 2000a; Smith *et al.*, 2008), so even at relatively low stocking densities sheep grazing can have a large impact on limestone pavement biodiversity.

4.4.1 <u>Grazing and Species Frequency</u>

In this study, the relationship between grazing and biodiversity on limestone pavements was examined using three parameters which were measured at each site. These were *sward height*, *emergent height* and a subjective *grazing intensity* score.

The key measure was height of the sward on, or immediately adjacent to, the limestone pavement. Here it was presented as a surrogate for grazing intensity for the following reasons:

- Recent evidence has established that sward measurement is a reliable measure for estimating grazing intensity in all types of the common grazers including sheep, rabbits and cattle (Smith *et al.*, 2008).
- Sward height provided objective measurement data. The parametric nature of this measurement data allowed for a more thorough statistical analysis than ordinal data.
- Sward height correlated closely with the two other grazing assessment measurements being used in this study, namely (a) the height above the

grikes of emergent vegetation and (b) the subjective 'grazing intensity' rating (based on evidence seen on site including animals seen, scats observed etc.).

The relationship between sward height and species richness was analysed using SPSS analytical software (SPSS for Windows, 2005). Sward height raw data were not normally distributed so square root transformations were used. Data then showed a normal distribution (Kolmogorov-Smirnov test, p>0.05) and demonstrated a statistically significant positive correlation with species richness (r=0.371, p=0.01, n=46). This suggests that the number of species present on limestone pavement declines where mean sward height is lower and therefore with increased grazing intensity. Investigating the hypothesis that species richness is dependent on sward height concluded that although there was a statistically significant relationship between these variables, the R^2 value of 0.14 suggested that only a part of the complex factors that determine biodiversity on limestone pavements has been explained.

4.4.2 Grazing and Rare Species

Species richness does not tell the full story, as previously discussed, so the relationship between the presence of the rarer floral species was examined against sward height (transformed as in 4.4.1) as it is these species that rely on limestone pavement for their continued existence. There was a highly statistically significant positive correlation between sward height and rare species ('A' and 'B' species), (r=0.399, p=0.006, n=46). This therefore indicated a strong relationship between increased grazing intensity and reduction in the presence of the rarer, pavement-dependent species.

Table 4-5: ANOVA of simple regression between sward height (as a surrogate for grazing intensity) and rare pavement species showed that a higher grazing intensity significantly contributed to a reduction in 'A' and 'B' species (R^2=0.279).

ANOVA	Sum of Squares	df	Mean Square	F	Sig.
Regression	156.411	1	156.411	17.001	.000
Residual	404.806	44	9.200		
Total	561.217	45			

Table 4-5 describes the relationship between rare species and sward. It confirms that numbers of rare species were increased where mean sward height was greater (i.e. grazing levels were lower), and this explained 28% (R^2=0.279, $p<0.01$) of the relationship between the two factors.

4.4.3 Grazing and Ruderals

Certain floral species are known to be associated with unsustainable farm management practices, as discussed earlier, so it would seem appropriate to explore the hypothesis that there may be a relationship between the 'negative 1' species (including Thistle, Nettle etc.) and grazing pressure, as represented by mean sward height. There was a negative association between these two variables but no conclusions could be drawn as it was not statistically significant ($p>0.05$).

4.4.4 Multivariate Analysis of Grazing Intensity

A more detailed picture emerged using multivariate analysis of the relationship between limestone pavement flora and grazing intensity, using PC-ORD (as Section 4.3).

Figure 4-11 uses NMS to investigate the relationship between total plant species composition and grazing intensity on all 46 limestone pavements. Pavement stands are labelled and colour coded (see Figure 4-11 caption) according to the subjective assessment of grazing level conducted during field visits. It includes all types of grazing i.e. sheep, cattle, rabbits and other grazers such as deer or goats. Results show that similarities in limestone pavement species composition clearly group in the ordination space according to the intensity of the grazing at the sites. It is possible to put a theoretical 'threshold' (Figure 4-11) onto the ordination to indicate the impact on plant communities related to higher and lower levels of grazing intensity.

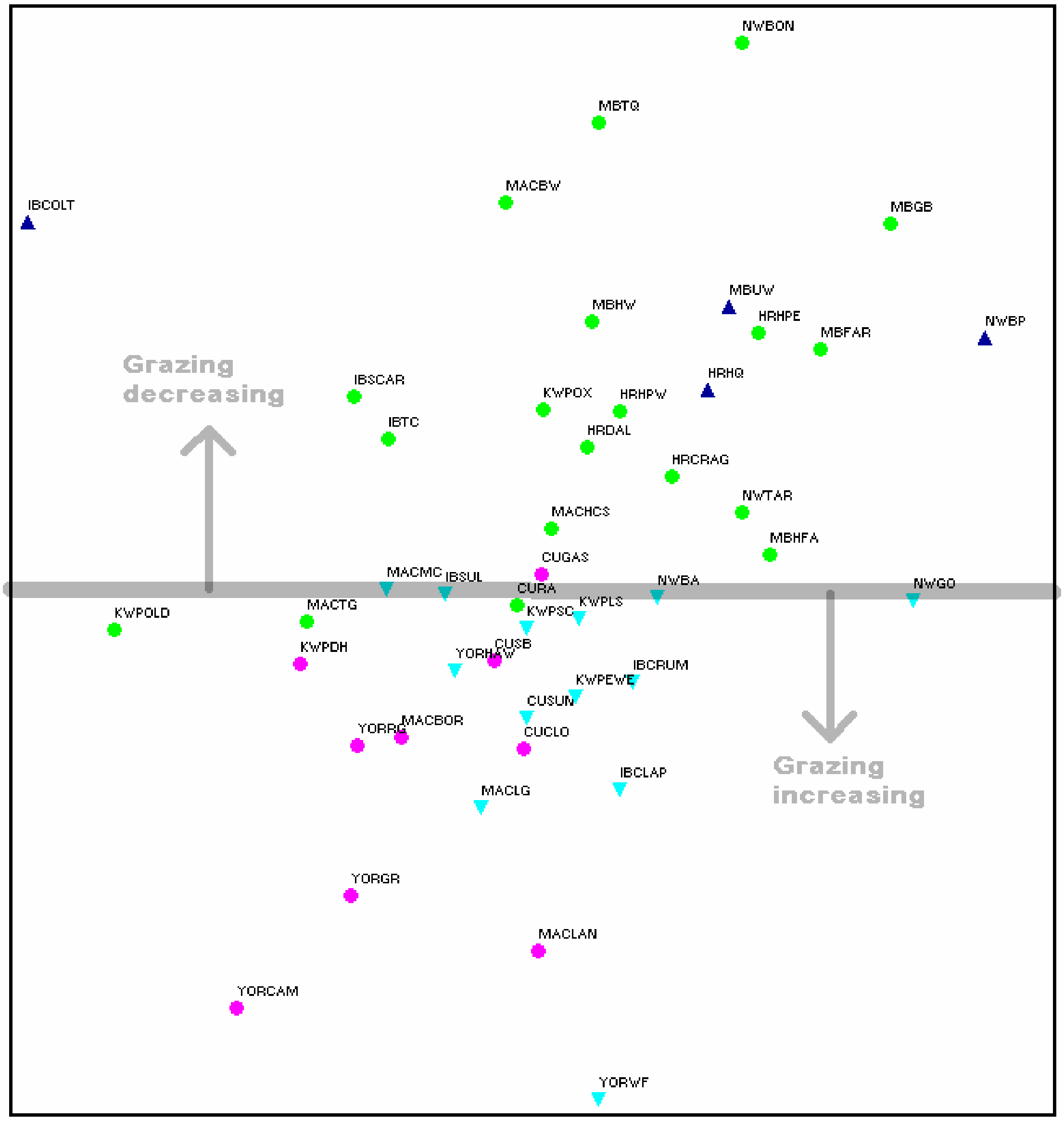

Figure 4-11: Ordination of similarity between stands based on total species composition using NMS. Pavements are coded according to grazing intensity where ▲=no grazing; ●=light grazing; ▼=medium level grazing and ●=high level grazing. The horizontal line indicates a "grazing threshold" between more heavily grazed below and more lightly grazed pavements above. Moelfre was removed as it was outlying the analysis.

4.5 Emergent Species

Emergent species, in the context of this research, are those plants, shrubs and trees that project above the top of the grikes on the limestone pavements. The height of vegetation emerging from grikes is generally accepted to be an indication of grazing intensity (JNCC, 1997; Smith *et al.*, 2008), as heavily grazed pavement stands are often devoid of flora that is unprotected by the grikes (see Figure 4-9).

Figure 4-12: Scrub developing on Holme Park Fell, following the exclusion of stock seven years previously (photograph taken 20th August 2007).

The nature and structure of the emergent vegetation also act as clues to the history of the grazing and management at the site. Limestone pavements with a long history of animal exclusion, such as Colt Park, Ingleborough, display dense mature woodland flora (Wagstaff, 1991). Holme Park, on Farleton Fell (Figure 4-12), was heavily grazed until 2000 when stock were excluded under new National Trust ownership (National Trust, 2003; Skelcher, 2001). Since then scrub has begun to develop and was observed during field survey, and previously bare pavement sites are now showing signs of vegetation cover.

In order to measure the overall nature and height of vegetation existing above grike level on each pavement, recording was made during field visits of the five tallest species along with their vegetation category. The results of this are presented in Figure 4-13.

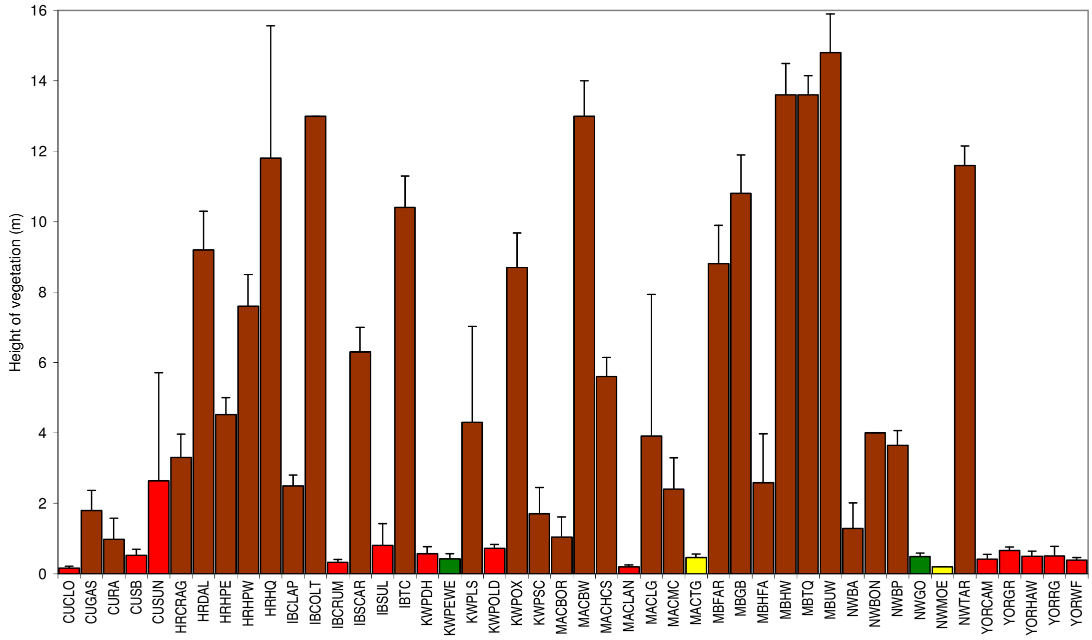

Figure 4-13: Mean height of species emerging above the top of the grikes on each limestone pavement with standard deviation indicated by positive error bars. Pavements are alphabetical and colour coded according to the tallest category of vegetation present (modal), where: ■ = tree; ■ = grass/sedge; ■ = herb; and ■ = negative species (Nettle, Thistle, Bracken and Gorse).

Ash (*Fraxinus excelsior*) was the emergent species found on the limestone pavements most frequently, noted on 31.3% of the 230 recordings. Interestingly, the second most commonly seen emergent species was Nettle (*Urtica dioica*) (12.6% of recordings). The third commonest species that was emergent above the grikes was Hawthorn (*Crataegus monogyna*), accounting for 11.3% of the recordings on the 46 limestone pavements.

Pavement stands that have trees as their modal emergent species with a mean height in excess of 8m are the traditional ‘wooded or part-wooded pavements’, presented clearly in Figure 4-13. These are Dalton Crags, Holme Park Quarry, Colt Park, Top Cow, Oxenber Wood, Bastow Wood, Farrar’s Allotment, Gait Barrows, Hampsfield Wood, Trowbarrow Quarry, Underlaid Wood and Taranau.

The hypothesis that there was no significant association between pavements, according to the nature of their modal emergent species, was examined. Chi square analysis conducted on pavements grouped by their emergent species type and the presence of ‘A’ and ‘B’ species showed no statistically significant difference between observed and expected numbers of rare species between groups.

Table 4-6: ANOVA considering modal emergent type as the grouping variable. Post hoc analysis demonstrates that both sward height and mean soil depth within the grikes are highly statistically significantly different between the wooded group and the ruderals group (p<0.01).

ANOVA		Sum of Squares	df	Mean Square	F	Sig.
Sward height	Between Groups	32.559	3	10.853	5.851	.002
	Within Groups	77.912	42	1.855		
	Total	110.471	45			
Mean soil depth	Between Groups	1088.646	3	362.882	6.547	.001
	Within Groups	2328.118	42	55.431		
	Total	3416.764	45			

However, there were statistically significant differences between those pavements with predominantly trees as their emergent species and pavements with mainly 'negative' species against two key surrogate grazing measures; sward height and soil depth. These results are presented in Table 4-6.

This simple assessment of limestone pavement, i.e. noting the flora type and height of the five tallest emergent species on each limestone pavement, has the potential to be used as a basic monitoring tool to gauge whether grazing levels are appropriate on limestone pavement. Statistical analysis indicated that where negative pavement species (Nettle, Thistle, Bracken and Gorse) were the tallest modal emergent species from the grikes on the pavement, the mean sward height declined and grike soil depth increased, all factors suggestive of sub-optimal management of the site. The use of such a simple monitoring technique may be of value to conservation agencies and will be discussed further in Chapters 6 and 8.

4.6 Floral Analysis using MAVIS Computer Software

Additional analysis on the plant species on the limestone pavements was performed using MAVIS (Modular Analysis of Vegetation Information System). This allowed closer analysis of the species composition of the plant communities by classifying according to the *Countryside Vegetation Scheme* (CVS); Grime's (1979) triangular *CSR model*; the *Ellenberg* scoring system for

Light, Fertility, Wetness and pH; and the *National Vegetation Classification* (NVC). MAVIS is a useful classification system which attempts to describe the distribution of plant species at different scales allowing site to site comparison to be made (Centre for Ecology and Hydrology, 2000). It should be noted that the methodology used in this study did not involve replicate samples from each site, so was incompatible with the NVC classification (Rodwell *et al.*, 1992) and this aspect of the analysis was therefore redundant. The CVS classification groups vegetation into 100 vegetation classes with similar botanical composition based on multivariate analysis of paired sample plots (Bunce *et al.*, 1999). Grime's CSR classification (summarised in Table 4-7) provides functional groupings of species based on their genetic characteristics and life history strategies.

Table 4-7: Grime's C-S-R model (after Grime *et al.,* 1988).

Intensity of disturbance ↓	**Intensity of stress →**	
	Low	**High**
Low	Competitors	Stress-tolerators
High	Ruderals	(no viable strategy)

It is a three strategy model based on the works of Ramenskii (1938) and Grime, Hodgson, and Hunt (1988). Competitors are plants which grow vigorously and compete well with neighbours trying to capture the same unit of resource. Stress-tolerators are able to withstand constraints such as periods of drought and low nutrient levels and ruderals are the weedy species that are early colonisers and prefer open, disturbed conditions (Grime, 2002). Lastly MAVIS incorporates the Ellenberg scoring system. This assigns values to communities of plants representing their affinities to key environmental conditions which include light, wetness, pH and fertility. Low light scores are consistent with shade-loving plants (scores equal to or less than 5), while scores over 6 indicate plants preferring well-lit conditions. Wetness scores indicate the degree of moisture content in soils that plants can tolerate, with the higher numbers denoting wetter substrates.

Table 4-8: Summary scores from analysis using the MAVIS computer package (CEH, 2000). Pavements are presented in alphabetical order.

	Ellenberg Scores				Grime's C-S-R			
	Light	Wetness	pH	Fertility	Competitors	StressTol	Ruderals	CVS Class
CUCLO	6.2	5.4	6.2	4.5	2.37	3.19	1.85	36
CUGAS	6.3	5.4	6.1	4.5	2.56	3.04	1.72	35
CURA	6.4	5.5	5.8	3.9	2.16	3.49	1.65	65
CUSB	6.2	5.3	6.1	4.3	2.34	3.19	1.88	35
CUSUN	6.2	5.4	6.1	4.4	2.29	3.39	1.64	39
HRCRAG	5.9	5.3	5.9	4.2	2.46	3.32	1.43	35
HRDAL	6.1	5.2	6	4.4	2.38	3.3	1.62	35
HRHPE	6.1	4.9	6.2	4.4	2.53	3.24	1.56	35
HRHPW	6.1	5.2	6.1	4.3	2.33	3.26	1.78	35
HRHQ	6.3	5	6.1	4.4	2.52	3.17	1.67	35
IBCLAP	6.1	5.2	6.1	4.5	2.42	3.04	1.96	24
IBCOLT	5.7	5.6	6	5.1	2.47	2.8	2.31	46
IBCRUM	5.9	5.4	5.8	4.2	2.36	3.32	1.61	36
IBSCAR	6.4	5.5	5.8	4.2	2.46	3.11	1.88	50
IBSUL	6	5.4	6.1	4.7	2.41	3.21	1.76	35
IBTC	6.2	5.5	6.1	4.5	2.4	3.08	2.08	50
KWPDH	6.5	5.5	6	4.3	2.49	3.02	2	46
KWPEWE	6.2	5.7	6.2	4.5	2.24	3.14	2	16
KWPLS	6.2	5.2	6.1	4.2	2.21	3.45	1.63	35
KWPOLD	6.2	5.3	6.3	4.7	2.49	3.1	2.05	34
KWPOX	6.2	5.2	6	4	2.07	3.6	1.58	35
KWPSC	6.2	5.2	6.1	4.4	2.34	3.26	1.74	35
MACBOR	6.3	5.5	6	4.5	2.2	3.2	2.07	50
MACBW	6.1	5.3	5.8	4.6	2.53	3.09	1.82	35
MACHCS	6.2	5.3	6.1	4.4	2.49	3.2	1.63	35
MACLAN	6.5	5.5	6.1	3.9	2.2	3.3	1.95	34
MACLG	6.4	5.4	5.7	4.1	2.06	3.39	2.03	35
MACMC	6.6	5.3	6.2	4.8	2.57	2.86	2.24	25
MACTG	6.5	5.5	6.1	4.3	2.22	3.11	2.26	48
MBFAR	6.3	5.2	5.9	4.2	2.38	3.27	1.73	35
MBGB	6.2	5.3	5.8	4.1	2.42	3.46	1.46	35
MBHFA	6.2	5.1	6	4.2	2.44	3.23	1.7	35
MBHW	6	5.2	5.9	4.5	2.5	3.34	1.68	35
MBTQ	5.8	5.3	6.1	4.7	2.6	3	1.7	35
MBUW	6	5.1	6	4.3	2.6	3.27	1.53	35
NWBA	6.3	5	6.2	4.2	2.35	3.16	1.84	21
NWBON	6	5	5.9	4.3	2.33	3.38	1.63	35
NWBP	6.3	5.1	6	3.9	2.32	3.39	1.73	35
NWGO	6.2	5	6.2	4.2	2.12	3.65	1.46	21
NWMOE	8	6.5	5.2	3.9	3	3	3	43
NWTAR	6.2	5	5.8	4.2	2.39	3.33	1.64	35
YORCAM	6.8	5.3	5.9	3.8	1.95	3.52	2.14	43
YORGR	6.7	5.4	5.8	4.1	2.06	3.33	2.15	61
YORHAW	6.4	5.4	6.1	4.4	2.4	3	1.89	36
YORRG	6.2	5.7	6	4.5	2.54	2.85	2.19	28
YORWF	6.5	5.5	5.7	3.5	1.67	3.67	2	64

The pH scores indicate soil acidity whilst the fertility value represents the nitrogen levels in the soils, where 5 is average and lower than this reflects nitrogen deficient soils (Hill *et al.*, 1999). The species lists were entered into the computer package and the results are summarised in Table 4-8. As limestone pavements are an extremely specialised habitat the CVS has a limited role in its classification. Pavement species aggregated (50%) to Class 35 (diverse base-rich woodland/hedges) commonly containing Hazel (*Corylus avellana*), Blackthorn (*Prunus spinosa*) and Holly (*Ilex aquifolium*).

Other elements of the MAVIS computer package such as Ellenberg scores and CSR ratings provide useful classifications. Higher scores for light in the Ellenberg classification are found against the more open pavements, notably the Yoredales (Cam High Rd, Greensett and Wold Fell in particular), suggesting that their wide, shallow grikes do not house the shade-loving species communities associated with the more wooded pavements or those with deep grikes. More detailed analysis using MAVIS is found in Chapter 5 in relation to the holistic classification.

4.7 Line Intercept Sampling

The Line Intercept Sampling (LIS) offers a detailed 'snapshot' over ten metres across a habitat. It is of particular value where plants are sparsely distributed (Kent & Coker, 1992), as they are on limestone pavement, and it allows useful comparisons between pavements to be made.

Figure 4-14 visually represents the percentage of the LIS that is covered in vegetation and includes trees, shrubs, herbs, grasses and bryophytes within these estimates. All LIS were recorded during the flowering season between April and September (see Appendix A for exact timings) and LIS were positioned uniformly, in a perpendicular orientation to the pavement's main grike direction.

Multivariate analysis of the relationship between pavement flora and the percentage of vegetation on the LIS using NMS (as Section 4.3) indicated a statistically significant difference between sites in the amount of vegetation found on the clints (Figure 4-15).

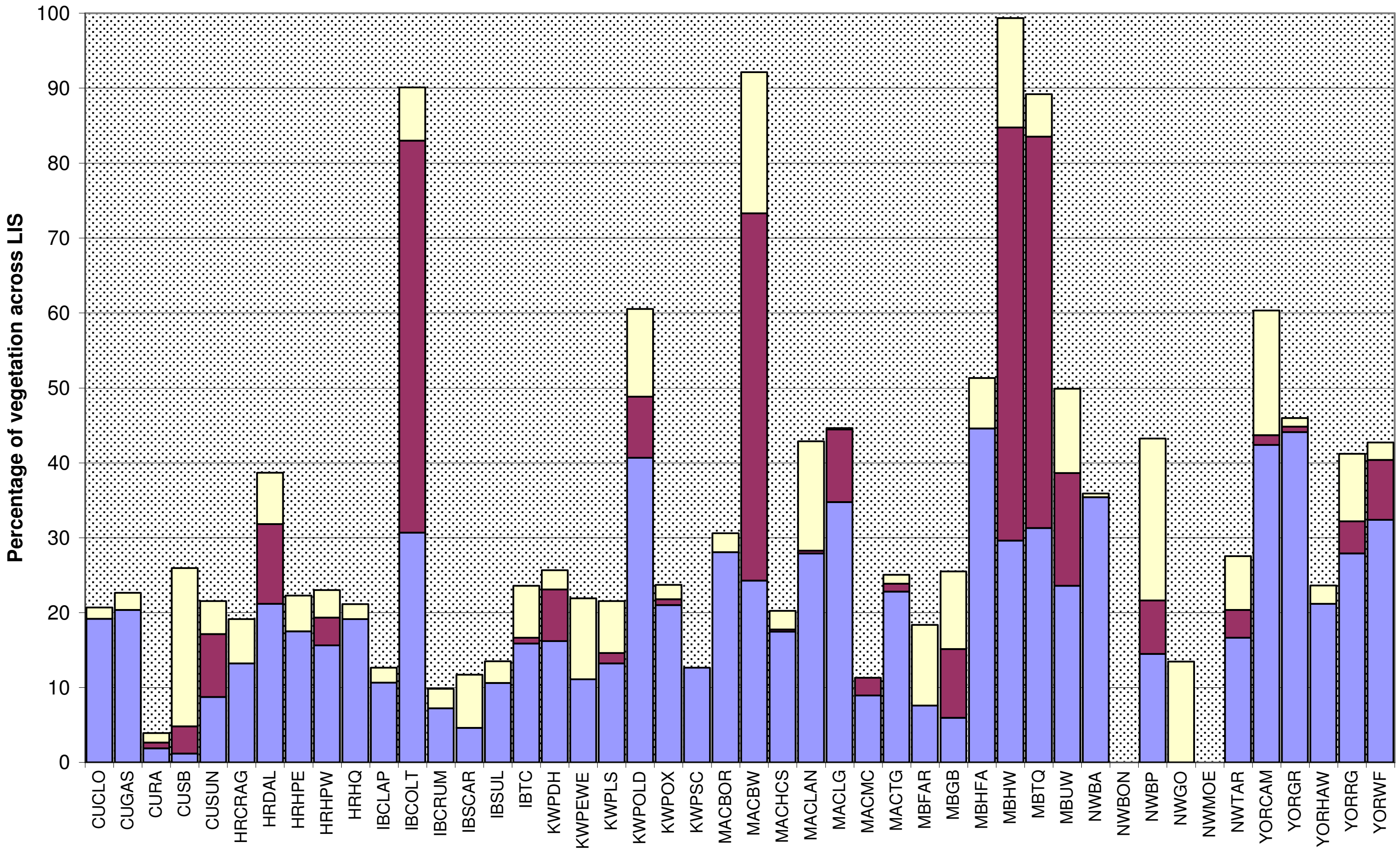

Figure 4-14: Quantity and location of the pavement vegetation on the ten metre LIS, where blue shows percentage vegetation in grikes; purple shows percentage vegetation on clints and beige indicates where vegetation is growing in solution features (runnels, pans etc.). LIS was not conducted on NWBON or NWMOE.

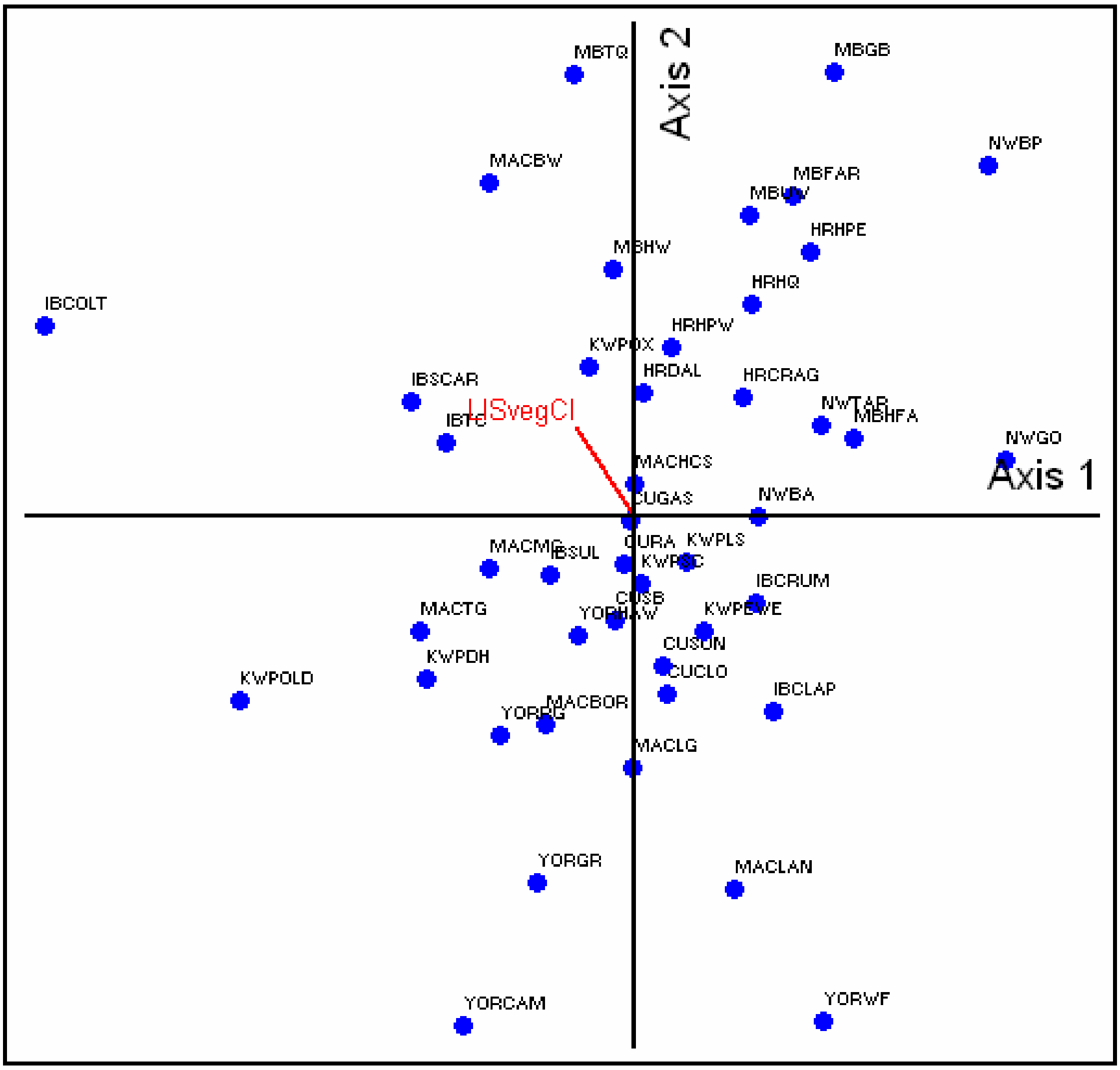

Figure 4-15: NMS ordination of flora present on 44 of the pavements (two outliers removed to avoid distortion) and its relationship with the abundance of vegetation present on the clints. Vector indicates the direction and strength of the relationship of the percentage of vegetation on the clints with both axis 1 and 2. Monte Carlo test indicated a 2-dimensional solution which resulted in a final stress score of 18.67, p=0.002, suggesting that it is a reasonable fit (Clarke, 1993; Kruskal, 1964).

The ordination was based on plant community dissimilarity and pavement stands with analogous plant compositions are seen to occupy nearby positions in ordination space. Subsequent bivariate correlation with axis scores then indicated which LIS data had a significant relationship with the gradients on the ordination. Overall, 23% of the variance in the distance matrix was explained by this distribution of vegetation on the limestone pavement. There was no other statistically significant relationship identified in the analysis of the LIS vegetation or substrate type.

4.8 Limestone Pavement Fauna

4.8.1 <u>Fauna Observed</u>

The informal observation of the fauna on limestone pavements during this research provided some interesting anecdotal evidence. However observations were entirely dependent on temperature, precipitation levels, seasonality and the level of the expertise of the observer. With the breadth of the remit of this work it soon became apparent that it was not possible to commit the time to the robust methodologies required to measure faunal populations on limestone pavements, even though this is an area of study that is long overdue (Burek & York, 2009; Cottle, 2004; Webb & Glading, 1998).

4.8.2 <u>Limestone Pavement Mollusca</u>

The exception to the above applies to the molluscan fauna of limestone pavements. With conchological expert Adrian Norris, 11 of the Yorkshire pavements were examined during 2008 as a case study to trial with the holistic classification. The results of this work have been analysed and are presented and discussed in Chapter 7.

4.9 Summary of Biodiversity Results

This chapter has examined limestone pavement biodiversity, considering relationships between biodiversity and limestone pavement area and the human impact on the biodiversity of the habitat with particular reference to its grazing history. It also investigated the composition of the plant communities on the limestone pavements, and the conservation value of a number of the plant species found there.

There was a statistically significant positive relationship identified between the size of the limestone pavement and both total number of floral species and rare ('A' and 'B') species observed on the 46 limestone pavements. Only 14% and 9% respectively of the difference in species richness and rare species presence could be explained by variation in limestone pavement size. This indicated that limestone pavement area was only one of the factors dictating plant communities on this habitat.

A total of 289 species were identified on the 46 limestone pavements visited. The total species count, which included higher plants, mosses and liverworts, ranged between 107 and 13 species per pavement. Of the top ten most species-rich limestone pavements, five are in NNRs with the other five protected within Sites of Special Scientific Interest.

There was a strong relationship demonstrated between species richness and numbers of rare ('A' and 'B') species recorded. Grike depth was established to be a significant indicator of increased presence of limestone pavement specialist species, illustrating that in general limestone pavements with deeper grikes had greater floristic conservation value.

The relationship between altitude and limestone pavement plant communities was examined and found to be a highly statistically significant influence on ordination axis scores. Further investigation, using bivariate correlation, deduced which individual higher and lower plant species were associated with both upland and lowland limestone pavements.

Grazing has historically been identified as being closely associated with the biodiversity of limestone pavements. In this research, a statistically significant positive relationship was identified between species richness and the height of the sward on limestone pavement. Additionally, a highly statistically significant relationship between rare limestone pavement species and sward height was identified. Examination of these relationships suggested that plant species, and particularly rarer species, had a close association with the height of the sward on the pavement. Sward height is accepted as a surrogate for grazing intensity on limestone pavement (Smith *et al.*, 2008) and this research would appear to confirm this theory.

It can therefore be concluded that grazing levels influence the species richness of limestone pavements and, in particular, high levels of grazing have a negative affect on those species with a high conservation value. The presence of ruderals (negative 1 species) on limestone pavement did not produce a significant relationship with sward height. Multivariate analysis of limestone pavement flora clearly illustrates the nature of the relationship between grazing levels and total species composition (see Figure 4-11). The significance of grazing as a factor in the holistic classification of limestone pavements will be explored further in Chapter 5.

The type and height of the five tallest plants and trees emerging from the grikes on each limestone pavement were recorded in this research. Ash (*Fraxinus excelsior*) was the modal tallest species on nearly a third of the limestone pavements in the study group (31.3%), with Nettle (*Urtica dioica*) (12.6%) and Hawthorn (*Crataegus monogyna*), the tallest modal emergent species on 11.3% of pavements.

Comparing limestone pavements with trees as their primary emergent species with limestone pavements where 'negative' species were the principal emergent species proved worthwhile. Analysis of variance (ANOVA) demonstrated that grazing levels (using mean sward height and mean soil depth as surrogate measures) were statistically significantly higher in the 'negative' species pavement group. It is therefore suggested that this simple assessment, i.e. measuring the five tallest plant species emerging from grikes on a limestone pavement, may have potential to be added to the monitoring tools used by conservation agencies and other organisations to gauge the appropriateness of grazing intensity on limestone pavements.

Classifying limestone pavements by their plant communities, using currently available plant classification schemes, gave limited results. Under the Countryside Vegetation Scheme (CVS), limestone pavement aggregates as Class 35, 'Diverse base-rich woodland/hedges'. Ellenberg scores and Grime's 'Competitor/Stress-tolerators/Ruderals' evaluation were also presented in this chapter for the 46 limestone pavements visited.

A 'snapshot' of each limestone pavement was recorded across 10m at the centre of each stand using a Line Intercept Sampling method, a technique not previously used for limestone pavement assessment. There was a statistically significant difference between the limestone pavements in the distribution of vegetation on their clints.

The results from the analysis in this chapter of the biodiversity on limestone pavements have provided valuable data. These were then used to inform the development of the holistic classification of limestone pavement that is presented in Chapter 5.

Pilot research into limestone pavement fauna was conducted at the beginning of this project. This indicated that the requirements to study fauna were more extensive than could be met within the remit of this research. The exception to this was the assessment of mollusc populations, and working with eminent Conchologist, Adrian Norris, field surveys were conducted on 11 Yorkshire limestone pavements in the study group, as a pilot case study. Results and analyses from this work are presented in Chapter 7.

5 HOLISTIC CLASSIFICATION OF LIMESTONE PAVEMENT

5.1 Introduction

The overall aim of this study was to produce a holistic classification of limestone pavements, according to both their geodiversity and biodiversity. The previous two chapters have considered the research data, collated over two years of fieldwork on 46 limestone pavements across North West England and North Wales, in a largely uni-disciplinary manner. In this chapter, the data were analysed collectively, and these results were combined with the geodiversity and biodiversity results in order to provide a holistic examination of the limestone pavements. This resulted in a classification for limestone pavement, which is presented in this chapter, along with details of the steps progressing towards the classification. Descriptions of the groups formed are also given, with analysis of the key factors which determined holistic group membership.

5.2 Development of the Holistic Classification

5.2.1 Methodology

The baseline used for the holistic classification of limestone pavement was the plant communities that were recorded on each of the 46 limestone pavement units. In this context, a community is simply a collection of plant species that were found at a specific defined time and place (McCune & Grace, 2002).
Using abundance of species as the basic response variable in community ecology is done on the understanding that species responses are not independent. For example, space for plant growth is limited, and so if space is taken up by one species it is therefore unavailable to another species. A logical analysis of community data must therefore consider this

interdependence, and multivariate analysis does this by studying the correlation structure of the response variables (McCune & Grace, 2002).

Nonmetric Multidimensional Scaling (NMS) was selected as the most appropriate tool for multivariate analysis of the geodiversity and biodiversity data collected. It is an ordination method well suited to ecological data that are non-normal or are on arbitrary, discontinuous, or otherwise non-standardised scales (Clarke, 1993; Kent, 2006) as was appropriate for the diverse nature of the environmental variables studied in this research. NMS offered analysis of the dissimilarities between stands based on their plant species composition and, together with secondary correlation with both quantitative and categorical environmental variables, allowed for the interpretation of the key drivers of limestone pavement ecology.

Outlier analysis identified that three limestone pavements, namely the small coastal pavement at Moelfre (NWMOE) and two wooded limestone pavements, Colt Park (IBCOLT) and Boncs (NWBON), had an unusual combinations of values for more than one of their variables. Due to the likelihood of this outlier effect strongly influencing the outcome of analysis (McCune & Grace, 2002) they were removed from the ordination.

The resultant holistic group classification was then compared, using analysis of the variance (ANOVA) around the group means or the Kruskal-Wallis comparison of group medians, to establish the key factors in the classification.

5.2.2 Multivariate Analysis

An NMS ordination was generated from a Sørensen (Bray-Curtis) similarity matrix of untransformed species presence/absence data using PC-ORD (McCune & Mefford, 2006) with a random starting configuration, and this is shown in Figure 5-1. A total of 43 limestone pavements from the study group were considered in this ordination with the three outliers removed. The ordination was based on plant community dissimilarity, so samples with analogous plant compositions are seen to occupy nearby positions in ordination space. Monte Carlo test indicated a two-dimensional solution, after 500 iterations, which resulted in a final stress score of 18.11, p=0.0001, indicating a reasonable fit (Clarke, 1993; Kruskal, 1964).

Post hoc assessment of the quality of the data reduction by ordination indicated that 66.6% of the original variation was represented by axis 1 (R^2=0.666) and 15.9% by axis 2 (R^2=0.159), with a cumulative 82.5% of the original variation represented.

Table 5-1: Pearson correlation coefficients (r) between ordination axis one and two scores (Figure 5-1) and measured environmental factors. The critical value for r is 0.297 at p<0.05 (* indicates significance) and is 0.384 at p<0.01 (indicates significance) (n= 43, df=42) (Fowler *et al.*, 2002).**

Description of Environmental Variable	Abbreviated name	AXIS 1		AXIS 2	
		r value	R-sq	r value	R-sq
Grike width (mean)	GwidthM	¯ 0.412**	0.17	¯ 0.146	0.021
Grike width standard deviation (s.d.)	GwidthSD	¯ 0.287	0.082	¯ 0.151	0.023
Grike depth (mean)	GdepthM	0.381*	0.145	¯ 0.171	0.029
Grike depth (s.d.)	GdepthSD	0.488**	0.238	¯ 0.205	0.042
Clint width (mean) - Sq. root transformed	CWidSqrt	0.132	0.017	0.026	0.001
Clint width (s.d.)	CwidthSD	0.08	0.006	¯ 0.014	0
Clint length (mean) - log transformed	ClenLog	0.131	0.017	¯ 0.12	0.014
Clint length (s.d.)	ClenSD	0.03	0.001	¯ 0.172	0.03
Clint perimeter (mean) - log transformed	CPeriLog	0.246	0.06	¯ 0.057	0.003
Clint perimeter (s.d.)	CperiSD	0.154	0.024	0.028	0.001
Runnel width (mean) - Sq. root transformed	SqrtRWid	¯ 0.009	0	¯ 0.094	0.009
Runnel width (s.d.) - log transformed	RWsdLog	¯ 0.074	0.006	0.179	0.032
Runnel length (mean) - Sq. root transformed	SqrtRLen	0.321*	0.103	0.05	0.003
Runnel length (s.d.) - log transformed	RLsdLog	0.284	0.081	0.118	0.014
Runnel frequency	Rfreq	0.358*	0.128	¯ 0.051	0.003
No. of clints per metre	Cper1m	¯ 0.175	0.03	¯ 0.032	0.001
No. of mineral veins per metre	MVper1m	0.124	0.015	0.204	0.042
Soil depth in grikes (mean)	Msoildep	¯ 0.454**	0.206	¯ 0.116	0.013
Soil depth in grikes (s.d.)	sdsoilde	¯ 0.273	0.075	¯ 0.056	0.003
Soil pH variability	varpH	0.027	0.001	¯ 0.103	0.011
Pavement Dip	Dip	0.551**	0.303	0.073	0.005
Pavement Slope	Slope	0.523**	0.273	¯ 0.041	0.002
Altitude (Height above sea level)	Altitude	¯ 0.919**	0.845	0.109	0.012
Quantity of litter found on site	Litter	¯ 0.037	0.001	¯ 0.18	0.032
Sward height - Sq. root transformed	SqrSward	0.733**	0.537	¯ 0.259	0.067
No. of fossil types	FossVar	¯ 0.177	0.031	0.103	0.011
Distance to major fault - Sq. root transformed	SqFault	¯ 0.59**	0.348	0.021	0
Distance to coast	CoastDis	¯ 0.713**	0.509	¯ 0.18	0.033
Height of emergent species	meanEm	0.712**	0.507	¯ 0.343*	0.117
Height of emergent species (s.d)	sdEm	0.232	0.054	¯ 0.128	0.016
Variability in type of emergent species	VariEm	¯ 0.262	0.069	0.206	0.043
Variability in grike orientation	VarGori	¯ 0.003	0	0.097	0.009
Windspeed (mean annual)	Windspd	¯ 0.223	0.05	0.425**	0.181
Annual precipitation	Precip	¯ 0.581**	0.337	¯ 0.154	0.024
Area (square metres) - Sq. root transformed	SqrtArea	¯ 0.357*	0.127	¯ 0.198	0.039
No. of days ground frost per annum	FrostPA	¯ 0.755**	0.569	¯ 0.218	0.047

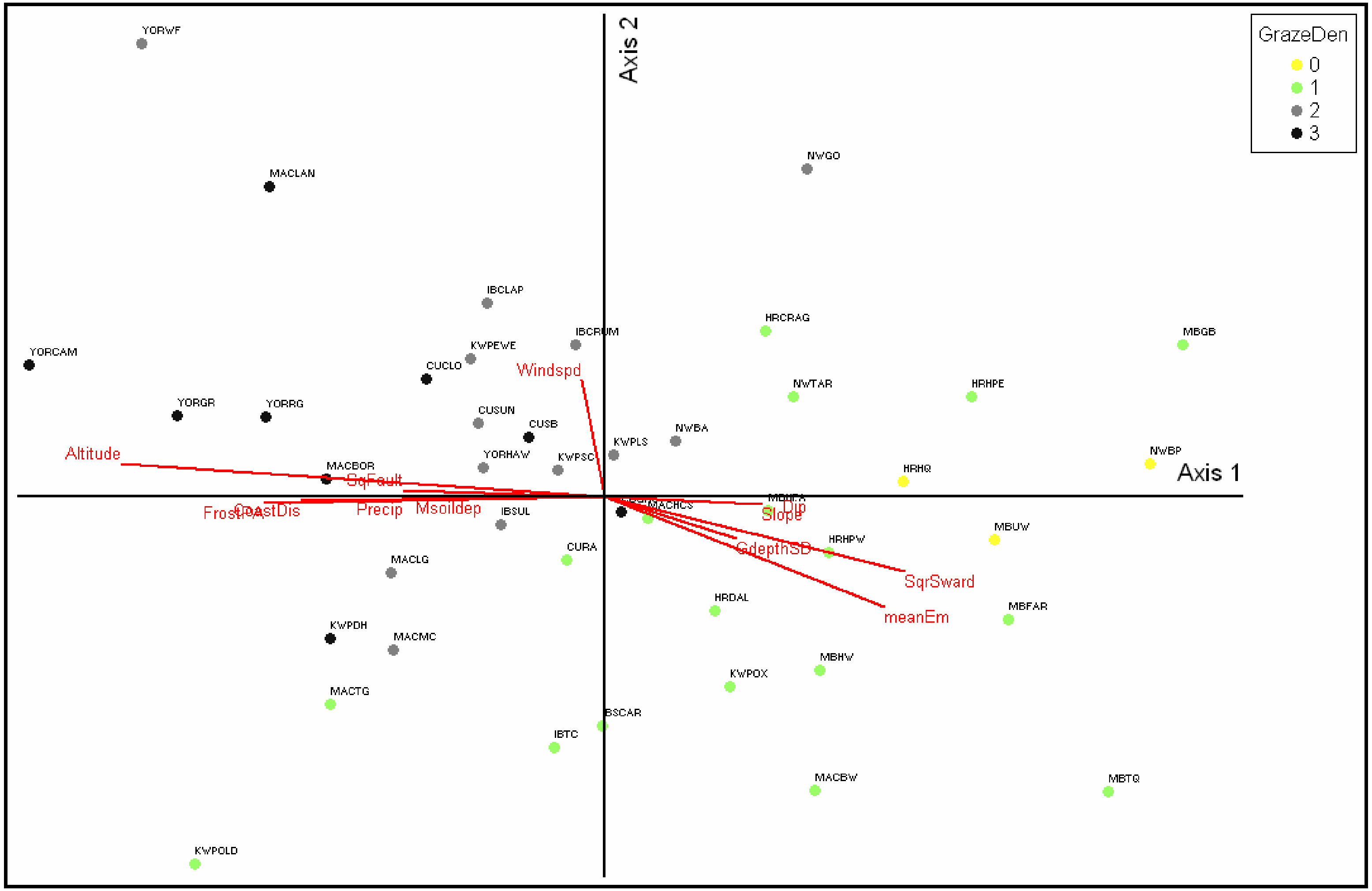

Figure 5-1: Ordination of similarity based on total species composition using NMS. Vectors indicate direction and strength of subsequent bivariate correlations of axis scores with environmental variables. Colour coding is by grazing categories, see legend, where 0=no grazing; 1=light grazing; 2=medium levels; 3=heavy grazing.

Bivariate correlation was then used to examine the strength and direction of the relationship between the ordination axis and 73 environmental factors. Environmental variables displaying a non-normal distribution were transformed prior to the correlations, as described in previous chapters. A summary listing the variables, transformations undertaken and their relationships with axis scores, is presented in Table 5-1.

The multivariate analysis grouped the limestone pavements in ordination space according to their plant communities. Subsequent bivariate correlation with axis scores then indicated which environmental variables had significant relationships with the gradients on the ordination (see directional vectors in Figure 5-1). The strongest environmental influence in the ordination was altitude of the limestone pavement, showing a very strong negative correlation with axis 1 (r=¯0.919), a relationship previously identified in both the geodiversity and biodiversity analyses in Chapters 3 and 4. Other landscape scale features which significantly influenced the gradient of the ordination were proximity of the pavement to the coast, pavement slope, and the size of the limestone pavement.

Climatic influences were also strongly correlated with the ordination axes, namely amount of frost days per annum, quantity of precipitation, and windspeed. Windspeed had the strongest positive correlation with axis 2 (r=0.425) along with height of emergent species (r=¯0.343) suggesting that exposure may be a factor having an effect on plant communities on limestone pavements. Some limestone pavement structural aspects were also influential, namely distance of pavement to a major geological fault, and limestone pavement dip. Opposing directional vectors along axis 1 in Figure 5-1 indicate the association between both the slope (r=0.523) and dip (r=0.551) of the limestone pavement and the proximity to a major fault (r=¯0.59). This illustrates the relationship that was previously identified in Section 3.2.3 which stated that pavements closer to a major fault show a significantly greater degree of slope and dip, as would be expected.

Geomorphological influences on the gradient of the ordination were depth of grikes, variability in the grike depth at each site, runnel frequency, grike width and runnel length.

Biodiversity variables which correlated highly statistically significantly with ordination axis scores were the height of emergent species, height of sward on the pavement (both showing significant effects on axis 1 scores, r=0.712 and r=0.733, respectively) and soil depth in the grikes. In Figure 5-1 the limestone pavements are coded according to the assessed level of grazing at the site. It can be seen that the pavements clearly group in ordination space in relation to the level of grazing intensity at the site; previously discussed in Chapter 4 and illustrated in Figure 4-11.

5.2.3 TWINSPAN Analysis

Having explored the data holistically using NMS, a 'two-way indicator species analysis' (TWINSPAN) (Hill, 1979) was then used to help find and define groups of limestone pavements. TWINSPAN also suggests indicator species for the classes that are formed. The benefit of classification of habitats, or functional grouping, is that it creates some order to vegetation that "shows endless variation in composition in time and space" (Miles, 1979).

The value of functional classification based on plant communities is a much debated topic (Goodall, 1973; Kent & Ballard, 1988; McCune & Grace, 2002) and the methodology even more so (Kent, 2006). The overall aim of this research was to further develop on the historical classifications that have been formulated for limestone pavements, based on either their geodiversity or biodiversity. This study aimed to produce holistic groupings that advance the understanding of the nature of this habitat, thereby aiding its ongoing conservation and management. With this concept in mind, although TWINSPAN had limitations (McCune & Grace, 2002), it was still the most widely used method for numerical classification (cluster analysis) in ecology (Kent, 2006) and was therefore assessed to be the most suitable tool.

A chart outlining the TWINSPAN groupings can be seen in Figure 5-2, using presence/absence plant community data, in PC-ORD (McCune & Mefford, 2006). TWINSPAN progressively divides the stands into two groups, as can be seen in the table, based on similarities in their plant communities.

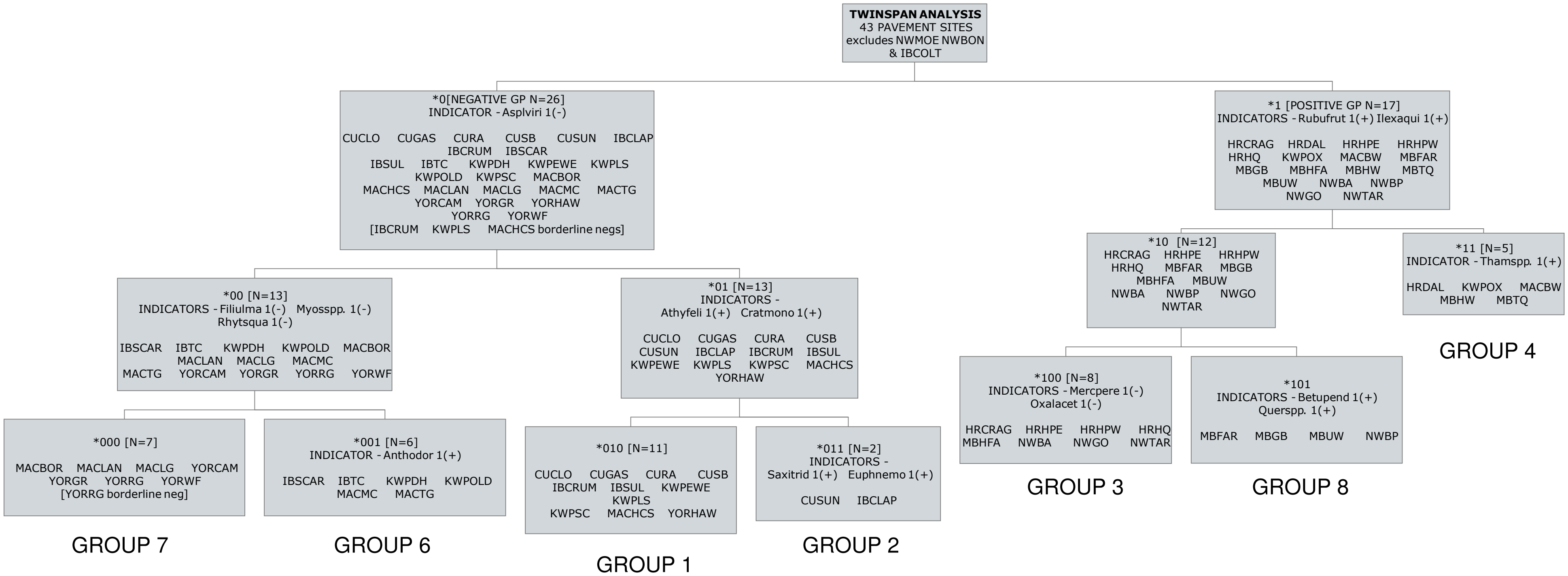

Figure 5-2: TWINSPAN tree of 43 limestone pavements with three outliers removed (Moelfre, Boncs & Colt Park Wood). Group 5 was assigned to Colt Park Wood.

TWINSPAN produced seven limestone pavement groups, with outliers Moelfre, Boncs and Colt Park Wood omitted, and so these pavements remain unclassified in this study. Colt Park Wood was assigned as a sole member of a notional Group 5. Arbitrary group numbers were assigned to the other six TWINSPAN groups formed (see Figure 5-2) and these groups were then analysed in depth to determine the significant differences defining each group. It is of note that one of the features of TWINSPAN is that when one group is relatively homogeneous it can leave a 'bucket' group of what remains. Therefore, some groups will be more similar in their characteristics than will others (McCune & Grace, 2002).

In the TWINSPAN analysis, Group 2 contained only two limestone pavement stands, proving too small a grouping to be viable alone. Group 1 and Group 2 were therefore re-amalgamated at the second division level and the resulting classification termed Group 1. This formed the largest group with 13 members, comprising of all the Cumbrian limestone pavements (The Clouds, Great Asby Scar, Royalty Allotment, Sayle Bottom and Sunbiggin) and a range of Yorkshire pavements, namely Crummack Dale, Sulber, Ewe's Top, Little Stainforth, Smearsett Copys, Hill Castles Scar, Hawkswick Clowder, and Clapdale Scars.

Subtleties of the holistic classification were unveiled by comparison of means or medians both between groups and within groups, using ANOVA or a similar non-parametric analysis (Kruskal-Wallis, Mann Whitney U Test) and by the use of post hoc tests.

5.3 Secondary Analysis of the Holistic Classification with Geodiversity Variables

The holistic classification was analysed using ANOVA to compare group means where the variables met the assumptions of parametric data, i.e. independent, normally distributed interval data with homogeneity of variance (Levene, $p>0.05$) or equality of means (Welch, $p<0.05$). Appropriate post hoc tests were conducted to compare all different combinations of group means. As sample sizes were unequal, Gabriel's pairwise test procedure was used where there was homogeneity of variance. Where there was heterogeneity of variance, post hoc tests were carried out using Games-Howell's multiple comparison procedure. This is also suitable in situations where group sizes are unequal (Field, 2005).

A summary table of geodiversity variables showing statistically significant differences in comparisons of their group means can be seen in Table 5-2. The differences defining the groups following post hoc procedures are outlined in Section 5.7.

There was no significant difference identified by ANOVA of group means in limestone pavement area, windspeed, depth of soil in the grikes, number of mineral veins, grike width/depth, clint metrics or in their runnel metrics.

Table 5-2: Comparison of geodiversity variable group means, using ANOVA. Variables met assumptions of ANOVA and results were significant at p<0.05.

Variable		Sum of Squares	df	Mean Square	F	Sig.
Distance to Fault (square root transformed)	Between Groups	11232.943	5	2246.589	3.867	.006
	Within Groups	21494.152	37	580.923		
	Total	32727.095	42			
Dip	Between Groups	1110.165	5	222.033	4.086	.005
	Within Groups	2010.440	37	54.336		
	Total	3120.605	42			
Altitude	Between Groups	519588.820	5	103917.764	18.135	.000
	Within Groups	212022.250	37	5730.331		
	Total	731611.070	42			
Slope	Between Groups	237.120	5	47.424	3.417	.012
	Within Groups	513.485	37	13.878		
	Total	750.605	42			
Distance to Coast	Between Groups	7926503255.3	5	1585300651.07	17.582	.000
	Within Groups	3336063785.4	37	90163886.091		
	Total	11262567041	42			
Precipitation	Between Groups	220982.897	5	44196.579	5.682	.001
	Within Groups	287822.219	37	7778.979		
	Total	508805.116	42			
Days Frost	Between Groups	10885.877	5	2177.175	13.280	.000
	Within Groups	6065.758	37	163.939		
	Total	16951.635	42			
Grike Depth - standard deviation	Between Groups	4807.644	5	961.529	4.043	.005
	Within Groups	8800.108	37	237.841		
	Total	13607.752	42			

Non-parametric geodiversity variables that violated the assumptions of ANOVA were analysed using the Kruskal-Wallis test (Kruskal & Wallis, 1952). In Table 5-3, Kruskal-Wallis results are presented for those variables where groups showed statistically significant differences in their median scores. The other non-parametric geodiversity variables that were assessed to have no statistically significant difference between groups were number of clints, clint length and perimeter standard deviations, and the total percentage of the LIS that consisted of solution features.

Table 5-3: Kruskal-Wallis results of geodiversity variable where a significant difference was evident between group medians. Result was significant at $p<0.05$ (df=5)

Kruskal-Wallis	Clint Width - standard deviation	pH	Total % of LIS=Grike	Total % of LIS=Clint/ Rubble
H	11.364	12.305	17.111	15.477
Asymp. Sig. (p-value)	.045	.031	.004	.009

5.3.1 Variance in Altitude

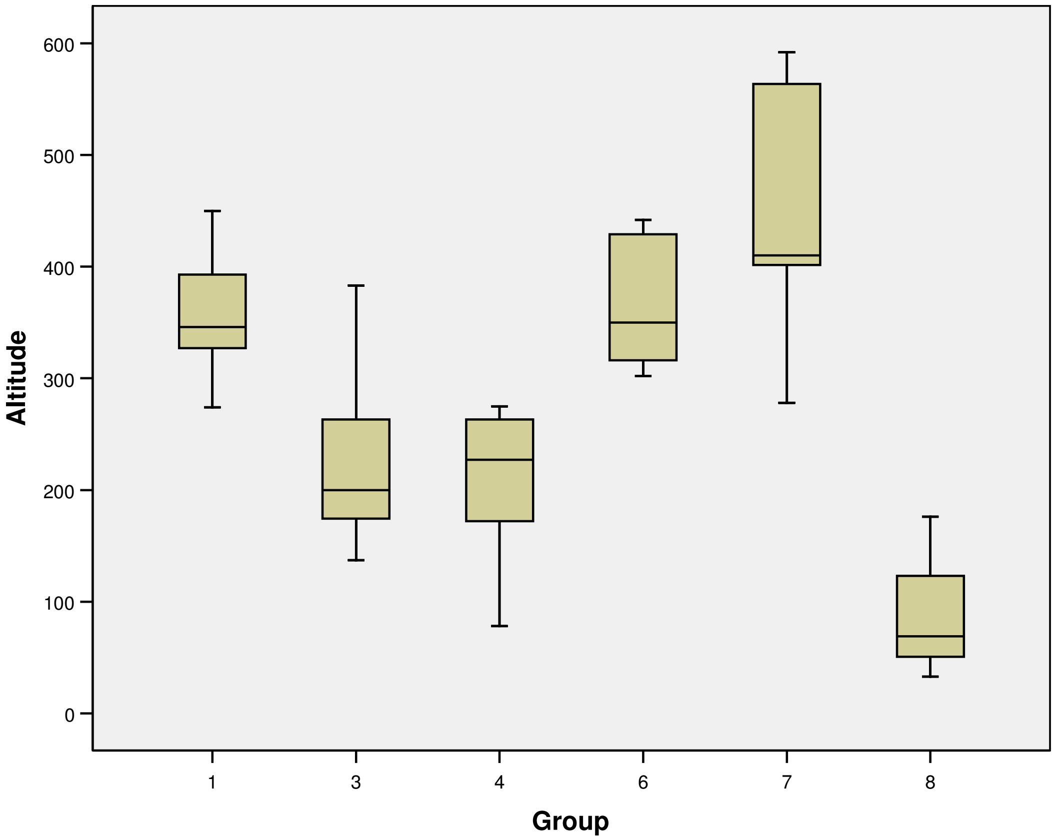

Figure 5-3: Boxplot representing altitude characteristics (in metres) between holistically classified limestone pavement groups. Each boxplot shows minimum, lower quartile, median, upper quartile and maximum values.

The ANOVA result for altitude was the factor that was most statistically significantly different between the limestone pavement groups (ANOVA, F(5,37)=18.135, p<0.001). Post hoc tests revealed that altitude was statistically significantly higher in the negative TWINSPAN groups (7, 6 and 1 respectively), which includes the Yorkshire, Lancashire and Cumbrian limestone pavements (Gabriel, p<0.05).

Figure 5-3 indicates the differences between groups in terms of their height above sea level and the variance within each group. The group with the highest mean elevation was Group 7 (458.57m, +/-116.43m) which largely comprises of the limestone pavements in the Yoredales. Group 8 had the lowest mean height above sea level (86.75m, +/-61.88m). It contains three wooded Morecambe Bay pavements (Farrar's Allotment, Gait Barrows and Underlaid Wood) with Bryn Pydew, a low altitude wooded pavement in North Wales.

5.3.2 Climate

With the difference between groups in their altitudes, an expected associated factor was the distribution of precipitation, as the volume of precipitation in the British Isles is known to increase over higher ground, such as the Pennine and Cumbrian Hills (Goudie & Brunsden, 1994). There was a significant difference in the amount of precipitation between groups (ANOVA, F(5,37)=5.682, p<0.001) with statistically significantly greater precipitation in Groups 6 and 7 (875.5mm and 871.0mm mean precipitation per annum, respectively) than in Group 3, which had the lowest mean precipitation at 675.5mm per annum (Gabriel, p<0.05).

Frost days showed a similar pattern of increase with altitude, though there were localised topographical variations, as would be expected in the UK (Goudie & Brunsden, 1994). The distribution of frost days per annum was found to be associated with altitude, and a statistically significant difference was established between Groups 6, 7 and 1 respectively, with the highest number of frost days, and Groups 8 and 3 respectively, with the lowest number of frost days (ANOVA, F(5,37)=13.28, p<0.001; Gabriel, p<0.05). This will increase freeze thaw action, breaking up clints and widening grikes through physical weathering (Trudgill, 1985a).

5.3.3 Coastal Proximity

A relationship between the proximity to the coast of the limestone pavements in this study and their altitude was identified in Chapter 3 (see Table 3-5) and ANOVA of group means again demonstrated a close association. Group 8 was in closest proximity to the coast (mean 2454m, +/-576m) and both Group 8 and Group 3 (mean 6064m, +/-4293m) were significantly nearer to the coast than Groups 1, 6 and Group 7, the last of which was furthest from the coast at 39981m, +/-9832m (ANOVA, $F(5,37)=17.582$, $p<0.001$; Games-Howell, $p<0.05$).

5.3.4 Structural Differences between Groups

Structural variation in limestone pavement also proved significant in analysis between the holistic groups, as differences were identified in their proximity to a major fault and the degree of their slope (Table 5-2), and closely related to this was the pavement dip. Group 4, a wooded group that includes Dalton Crags, Oxenber Wood, Bastow Wood, Hampsfield Wood and Trowbarrow Quarry, had the highest mean slope and dip at 9.2 degrees, +/-3.6 degrees; and 17.4 degrees +/-12.7 degrees, respectively.

5.3.5 Geomorphological Variance

Two elements of limestone pavement geomorphology were found to be of significant difference between two of the groups, namely grike depth standard deviation and clint width standard deviation. Variability around the mean for grike depth measurement was statistically significantly higher in Group 1 (mean 0.28m, +/-66.4mm) than Group 7 (mean 0.11m, +/-76.7mm) (ANOVA, $F(5,37)=4.04$, $p<0.01$, Games-Howell, $p<0.05$). In relation to clint width, variability around the median was higher in Group 6 than Group 7 (Kruskal-Wallis, $H=11.36$, $df=5$, $p=0.045$) with the post hoc test determining a significant difference between these groups (Mann Whitney, $U=2.0$, $p<0.01$).
Group by group analysis of the differences between the holistic classes in respect of their geodiversity and how it relates to the limestone pavement biodiversity will be explored in more detail in Section 5.7.

5.4 *Secondary Analysis with Biodiversity Variables*

Table 5-4: ANOVA of biodiversity variables by holistic groupings. Variables met assumptions of ANOVA and results were significant at p<0.05.

ANOVA		Sum of Squares	df	Mean Square	F	Sig.
Emergent Height	Between Groups	5522927.543	5	1104585.509	11.582	.000
	Within Groups	3528827.964	37	95373.729		
	Total	9051755.507	42			
Sward Height (square root transformed)	Between Groups	48.725	5	9.745	6.747	.000
	Within Groups	53.442	37	1.444		
	Total	102.167	42			
Species Richness	Between Groups	5018.932	5	1003.786	5.774	.000
	Within Groups	6432.743	37	173.858		
	Total	11451.674	42			
AB (Rare) Species	Between Groups	131.866	5	26.373	3.130	.019
	Within Groups	311.762	37	8.426		
	Total	443.628	42			
Negative1 Species	Between Groups	47.581	5	9.516	10.000	.000
	Within Groups	35.209	37	.952		
	Total	82.791	42			
No. Tree Species	Between Groups	234.174	5	46.835	11.147	.000
	Within Groups	155.454	37	4.201		
	Total	389.628	42			
No. Moss Species	Between Groups	234.174	5	46.835	4.335	.003
	Within Groups	399.733	37	10.804		
	Total	633.907	42			
No. Herb Species	Between Groups	2068.695	5	413.739	6.813	.000
	Within Groups	2247.072	37	60.732		
	Total	4315.767	42			
No. Fern Species	Between Groups	71.343	5	14.269	4.873	.002
	Within Groups	108.332	37	2.928		
	Total	179.674	42			
Ellenberg - Light	Between Groups	.858	5	.172	6.992	.000
	Within Groups	.909	37	.025		
	Total	1.767	42			
Ellenberg - Wetness	Between Groups	.906	5	.181	12.559	.000
	Within Groups	.534	37	.014		
	Total	1.439	42			
Ellenberg - Fertility	Between Groups	.888	5	.178	3.300	.015
	Within Groups	1.992	37	.054		
	Total	2.880	42			
Grime's - Competitors	Between Groups	.555	5	.111	4.178	.004
	Within Groups	.984	37	.027		
	Total	1.539	42			
Grime's - Ruderals	Between Groups	1.458	5	.292	17.664	.000
	Within Groups	.611	37	.017		
	Total	2.069	42			

Biodiversity variables that demonstrated statistically significant differences between groups are presented in Table 5-4. There was no statistically significant difference outlined by ANOVA of group mean soil depth.

5.4.1 Group Analysis of Species Richness and Rare Species

In the overall analysis of limestone pavement species richness investigated in Chapter 4, there was a relationship identified between the size of the 46 limestone pavements and the number of species recorded there (Figure 4-1). However, analysis using the holistic classification indicated that there was no significant difference in limestone pavement area between the six groups, yet there was a significant difference established between groups in relation to their species richness and the number of AB (rare) species present.

Group 6 was the most species-rich limestone pavement group (mean 78 species, +/-22 species) and it had the largest number of AB species present (plants dependent on the limestone pavement to maintain population numbers) with a group mean of 10 species, +/-5 species. Group 6 comprises six thickly-bedded Yorkshire limestone pavements, including Scar Close, Top Cow, Dale Head, Old Ing, Malham Cove and Tennant Gill. ANOVA of group mean species richness established that Group 6 was significantly different to the other Yorkshire/Cumbrian limestone pavement groups, namely Groups 1 and 7 (ANOVA, $F(5,37)=5.774$, $p<0.001$; Gabriel, $p<0.05$). With regards to the AB plants recorded on the limestone pavements, there was a statistically significant difference identified between mean species numbers in Group 1 compared with the group with both the lowest species richness and least AB species, Group 7 (mean 43 species, +/-10 species, and 4 species, +/-1 species, respectively) (ANOVA, $F(5,37)=3.13$, $p<0.05$; Games-Howell, $p<0.05$).

5.4.2 Emergent Height

ANOVA of mean emergent heights found a significant difference between the wooded group, Group 4, and the three Yorkshire/Cumbrian groups (Groups 1, 6 and 7) (ANOVA, $F(5,37)=11.582$, $p<0.001$; Games-Howell, $p<0.05$). Group

4 had the greatest mean emergent height (11.62m, +/- 2.46m), with Group 7 the lowest (1.02m, +/-1.30m).

5.4.3 Sward Height

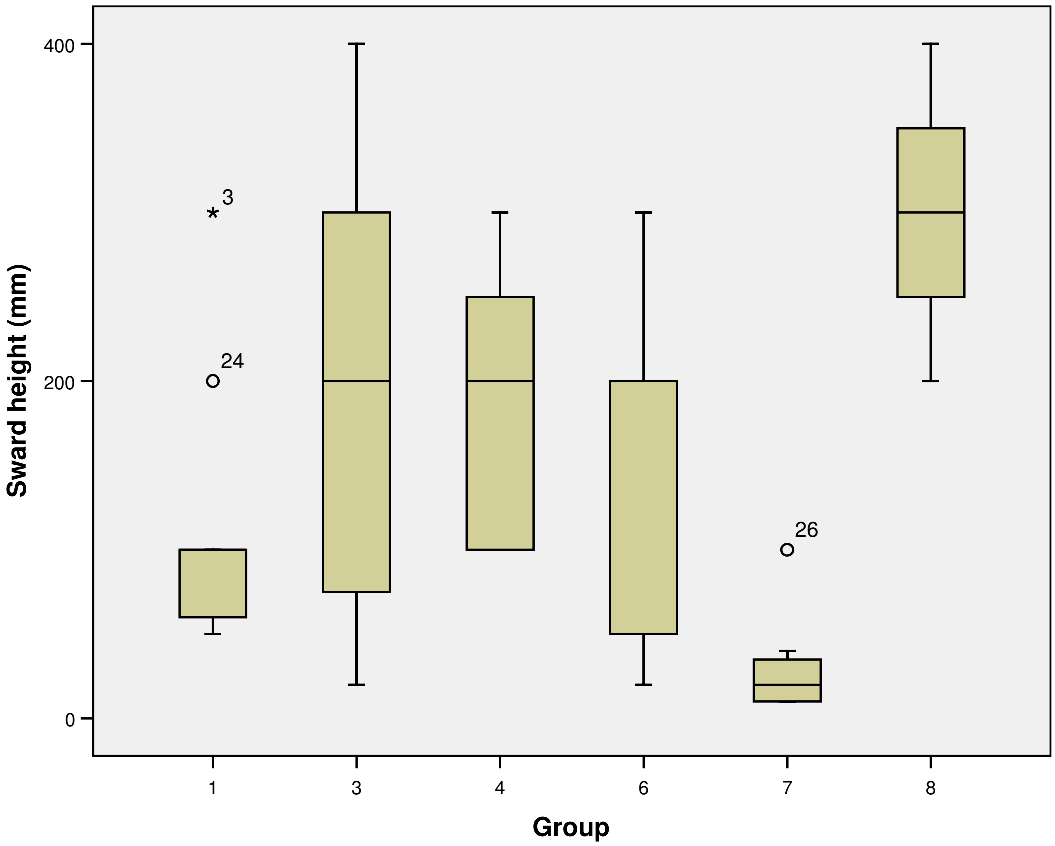

Figure 5-4: Boxplot representing sward height characteristics in the six limestone pavement groups using raw sward height measurements. Boxplots give minimum, lower quartile, median, upper quartile and maximum values. Three outliers are indicated: in Group 1, 3=Royalty Allotment; 24=Hill Castles Scar and, in Group 7, 26=Lea Green.

Analysis of variance in group sward height (square root transformed) provided a complex picture. To illustrate this, group medians are represented by boxplots in Figure 5-4, and these indicate a large degree of variability around the median in the majority of the limestone pavement groups, and particularly in Group 3. This group comprises the four non-wooded Hutton Roof limestone pavements and the North Wales limestone pavements with the exception of the wooded pavement at Bryn Pydew. In this group, sward height measurements ranged from 20mm on Bryn Alyn, a heavily sheep-grazed limestone pavement, to 400mm on Holme Park West, where grazing had been removed in 2000, seven years prior to this survey. The group with the lowest sward height was Group 7 (mean 31.4mm, +/-32.4mm). Six limestone pavements in Group 7 had a mean sward height value of 40mm or less, with the other limestone pavement in this group, Lea Green, recording only 100mm mean sward height.

Table 5-5: Multiple post hoc comparison of ANOVA of square root transformed sward height group means using the Games-Howell test. * indicates mean difference is significant at the p<0.05 level.

					95% Confidence Interval	
(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
1	3	-1.008	0.659	0.655	-3.317	1.300
	4	-1.134	0.539	0.385	-3.220	0.953
	6	0.109	0.697	1.000	-2.573	2.791
	7	1.506*	0.394	0.018	0.218	2.794
	8	-2.317*	0.458	0.016	-4.130	-0.503
3	1	1.008	0.659	0.655	-1.300	3.317
	4	-0.125	0.769	1.000	-2.749	2.498
	6	1.118	0.887	0.800	-1.889	4.124
	7	2.514*	0.676	0.034	0.173	4.855
	8	-1.308	0.715	0.490	-3.792	1.175
4	1	1.134	0.539	0.385	-0.953	3.220
	3	0.125	0.769	1.000	-2.498	2.749
	6	1.243	0.802	0.646	-1.630	4.115
	7	2.639*	0.559	0.017	0.524	4.754
	8	-1.183	0.606	0.447	-3.485	1.119
6	1	-0.109	0.697	1.000	-2.791	2.573
	3	-1.118	0.887	0.800	-4.124	1.889
	4	-1.243	0.802	0.646	-4.115	1.630
	7	1.396	0.713	0.442	-1.295	4.088
	8	-2.426	0.750	0.092	-5.209	0.357
7	1	-1.506*	0.394	0.018	-2.794	-0.218
	3	-2.514*	0.676	0.034	-4.855	-0.173
	4	-2.639*	0.559	0.017	-4.754	-0.524
	6	-1.396	0.713	0.442	-4.088	1.295
	8	-3.822*	0.482	0.001	-5.682	-1.963
8	1	2.317*	0.458	0.016	0.503	4.130
	3	1.308	0.715	0.490	-1.175	3.792
	4	1.183	0.606	0.447	-1.119	3.485
	6	2.426	0.750	0.092	-0.357	5.209
	7	3.822*	0.482	0.001	1.963	5.682

Results from post hoc analysis of ANOVA can be seen in Table 5-5, indicating where there was a significant difference between groups. Group 8, with the greatest height of sward (mean 300mm, +/-81.7mm), had a significantly greater mean sward height than Group 1 (mean 105.4mm, +/-70.4mm). Group 7 had a significantly lower mean sward height than all the other groups with the exception of Group 6 (Games-Howell, $p<0.05$). It is relevant to note here that Group 7 limestone pavements also had the lowest mean species richness and the least AB species recorded, on average.

5.5 Grazing Intensity

The relationship between sward height and grazing intensity was discussed in Chapter 4 and low sward height was seen to be associated with high grazing levels on the 46 limestone pavements surveyed.

The hypothesis that there was no significant difference in observed grazing intensity between the six limestone pavement groups was therefore explored, using the Kruskal-Wallis test, a non-parametric test which compares the medians of multiple samples. The null hypothesis was rejected as there was a highly statistically significant difference between median levels of grazing intensity between groups (K-Wallis, $H=25.45$, $df=5$, $p<0.001$).

Groups 8 and 4 had the lowest levels of grazing, whilst all limestone pavements in Group 7 had medium or high levels of grazing. This directly corresponded with the height of sward analysis between groups, where Groups 8 and 4 had the highest mean sward height and Group 7 had the lowest. These results support the hypothesis that the sward height on the limestone pavement directly reflects grazing level, and is consistent with recent research on limestone pavements conducted by Smith, Sanderson, Rushton, Shiel, Grayson, Millward, Wilmore, Woodward, Bevan, and Wainwright (2008).

The relationship between the classification and grazing is shown in Figure 5-5, repeating the ordination from Figure 5-1 but with the limestone pavements shaded by their group membership for clarity. The ordination is based on dissimilarity in total plant species composition.

Factors related to grazing intensity including sward height (vector coded Sqsward), emergent height (vector coded meanEm) and grazing intensity (see legend) have a strong relationship with axis 1. The Yorkshire and Cumbrian groups (Groups 7, 6 and 1) are collectively more highly grazed than their lowland counterparts (Groups 3, 8 and 4) and this can be clearly distinguished in the ordination.

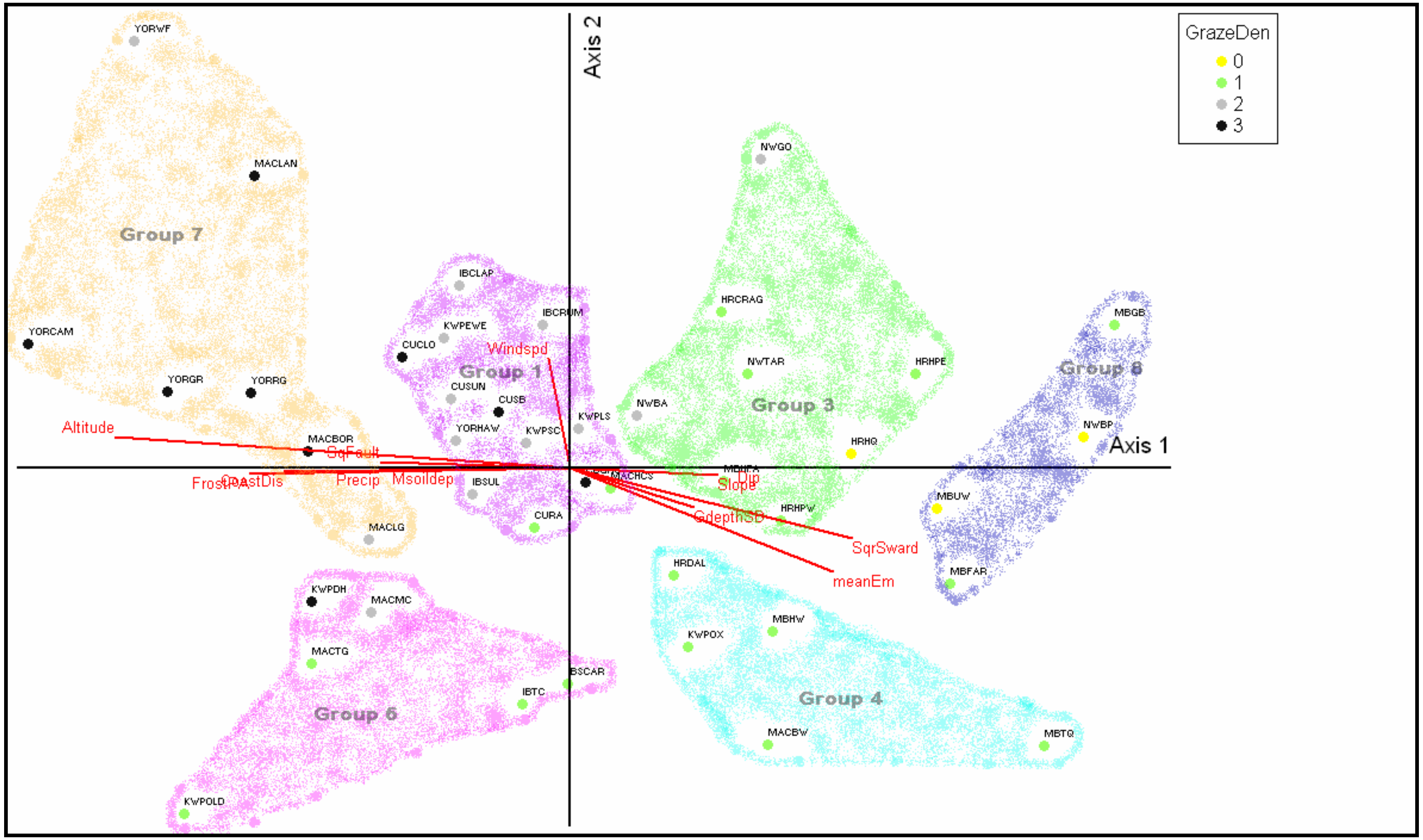

Figure 5-5: Ordination of 43 limestone pavements, previously presented in Figure 5.1, now shaded by their group classification. Axis 1 is strongly influenced by grazing indicators with the highest grazing intensity in Group 7, and the lowest in the two wooded classes (Groups 4 and 8). Colour coding of the limestone pavements is by grazing categories, see legend, where 0=no grazing; 1=light grazing; 2=medium levels; 3=heavy grazing.

5.5.1 MAVIS Analysis between Groups

A more detailed examination of the nature of the plant communities in each group, according to Ellenberg's and Grime's classifications, is seen in Figure 5-6. Ellenberg, defined a widely used set of indicator values for the vascular plants of Central Europe (Ellenberg, 1988; Hill *et al.*, 1999). Based on input from the plant community data from all limestone pavements in each group, and using the MAVIS computer package (Centre for Ecology and Hydrology, 2000), each holistically classified group produced a series of values which can be compared in Figure 5-6. These indicator values quantify the ecological conditions of a site by the range of tolerances of the plants found there with regards to light, moisture, soil pH and soil nitrogen levels (Ellenberg *et al.*, 1991).

Variations in the indicator values are subtle, as would be expected in comparisons between similar broad habitat types, but both Ellenberg and Grime's CSR scores are well respected, so are valuable as descriptive tools. Group 7 had the highest mean indicator value for light, statistically significantly higher than Group 4 (Mann Whitney, U=0.5, p=0.006). This suggests a plant community preferring a well-lit habitat, compared with Group 4 which had the lowest mean value for light indicators, reflecting a plant community preferring a semi-shade environment.

Wetness levels corresponded to the mean annual precipitation data at each site. Mean site pH scores were also lowest in Group 7, indicating that comparatively, this group had the most acidic soils. Fertility scores were highest in Group 8, indicative of sites with intermediate fertility levels, with lowest levels in Group 7, with a mean indicator value suggesting a habitat nearer to infertile, though these differences were not statistically significant.

Grime's CSR classification is a functional grouping of species based on their genetic characteristics and life history strategies. It is a three strategy model based on the works of Ramenskii (1938) and Grime (1974; 1977).

Competitors are plants which grow vigorously and compete well with neighbours trying to capture the same unit of resource. Stress tolerators are able to withstand constraints such as periods of drought and low nutrient levels (e.g. *Asplenium ruta-muraria* or ‘Wall rue’); and ruderals are the weedy species that are early colonisers and prefer open, disturbed conditions (e.g. *Stellaria media* or ‘Chickweed’) (Grime *et al.*, 1988).

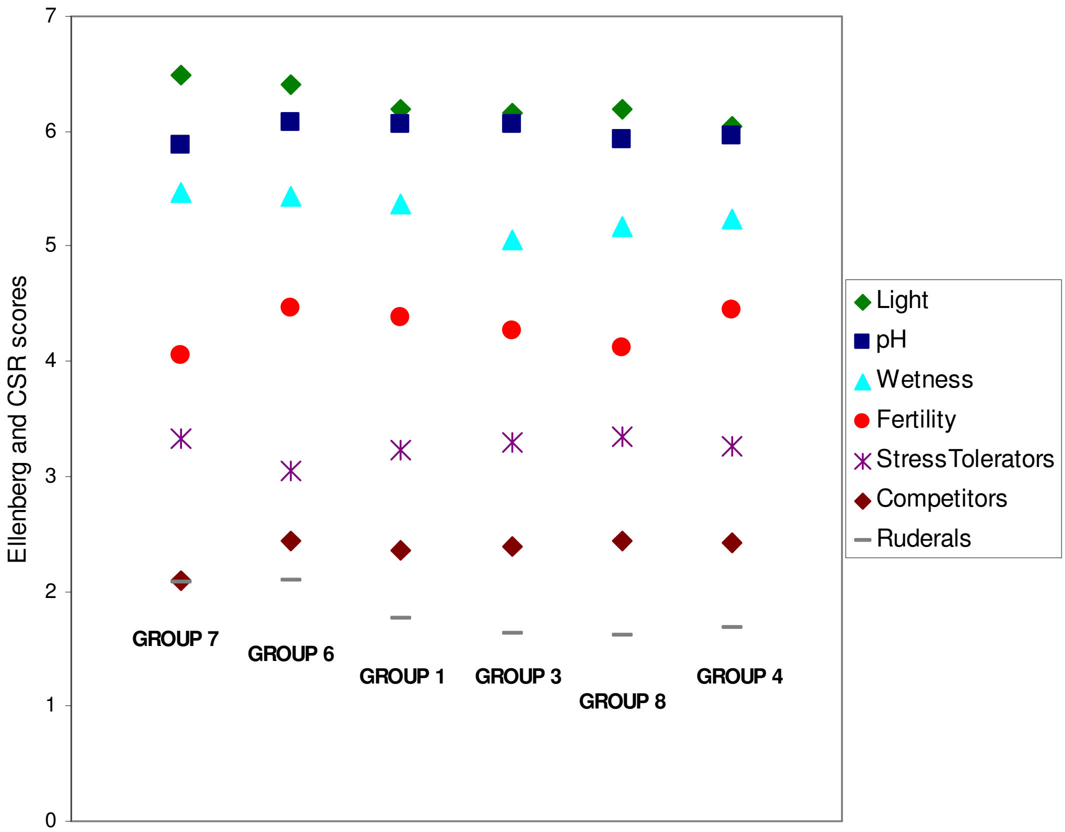

Figure 5-6: Mean summary scores from the analysis of plant species from each limestone pavement group using the MAVIS classification computer package (Centre for Ecology and Hydrology, 2000). This is a descriptive tool defining each group according to Ellenberg’s light, wetness, pH and fertility indicator values and Grime's CSR (competitors, stress tolerators and ruderals) model.

All groups scored highly for stress tolerators, unsurprising given the harsh, restricted limestone pavement environment (Silvertown, 1982). Mean competitor scores were also similar across groups, with the exception of Group 7 which had the lowest value, and statistically significantly lower than Group 6 scores (Mann Whitney, U=5.0, p=0.022). The Yorkshire/Cumbria groups (Groups 6, 7 and 1) had the highest mean ruderals score in Grime’s functional group model, possibly indicative of limestone pavements subject to more disturbance than the wooded pavements in Groups 4 and 8 which had lower mean ruderal values.

5.5.2 <u>Multivariate Analysis with Secondary Plant Variables</u>

An NMS ordination was generated from a Sørensen (Bray-Curtis) similarity matrix of untransformed species abundance data using PC-ORD (McCune & Mefford, 2006), as in Figure 5-1. A random starting configuration was used with data from 43 limestone pavements grouped by their classification.

Again, the ordination was based on plant community dissimilarity, with a Monte Carlo test indicating a two-dimensional solution, after 500 iterations, which resulted in a final stress score of 18.11, p=0.0001, indicating a reasonable fit (Clarke, 1993; Kruskal, 1964). Due consideration was given to the fact that plant variables were being re-analysed as they had already formed the basis of the TWINSPAN analysis for the classification.

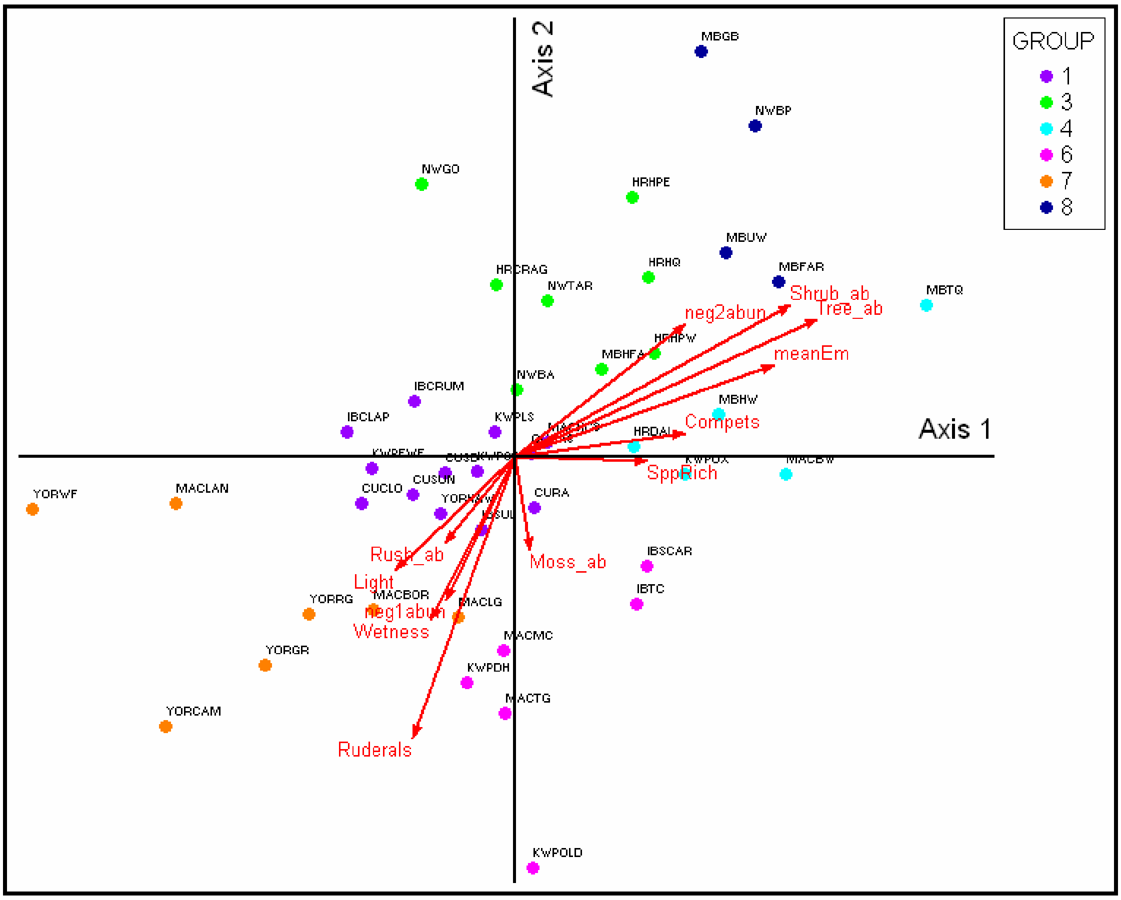

Figure 5-7: Ordination of similarity based on total species composition using NMS. Vectors indicate direction and strength of subsequent bivariate correlations of axis scores with secondary plant variables. Colour coding is by group membership (see legend).

Post hoc assessment of the quality of the data reduction by ordination indicated that 46.4% of the original variation was represented by axis 1

(R^2=0.464) with 36.1% represented by axis 2 (R^2=0.361), with a cumulative 82.5% of the original variation represented.

Bivariate correlation was then used to examine the strength and direction of the relationship between the axes and secondary plant variables, which included the Ellenberg and Grime's functional group scores discussed in Section 5.5.1. The Pearson correlation coefficient is listed in Table 5-6 in relation to Axis scores from the ordination. This highlights the factors which show a very strong association with Axis 1 scores, including tree and shrub abundance, mean emergent height, species richness, Grime's competitor scores and negative 2 species abundance (includes Gorse, Bracken, Beech, Cotoneaster, Red valerian and Western red cedar).

Table 5-6 Pearson correlation coefficients (r) between ordination axis one and two scores (Figure 5-1) and secondary plant variables. The critical value for r is 0.297 at p<0.05 (* indicates significance) and is 0.384 at p<0.01 (indicates significance) (n=43, df=42) (Fowler *et al.*, 2002).**

Description of Plant Variable	Abbreviated name	AXIS 1		AXIS 2	
		r value	R-sq	r value	R-sq
Tree species abundance	Tree_ab	0.822**	0.676	0.556**	0.31
Shrub species abundance	Shrub_ab	0.786**	0.617	0.583**	0.339
Sedge species abundance	Sedge_ab	0.335*	0.112	¯ 0.032	0.001
Rush species abundance	Rush_ab	¯ 0.397**	0.157	¯ 0.44**	0.193
Grass species abundance	Grass_ab	0.213	0.045	¯ 0.141	0.02
Sedge/Rush/Grass combined abundance	S+R+G_ab	0.2	0.04	¯ 0.187	0.035
Moss species abundance	Moss_ab	0.177	0.031	¯ 0.459**	0.211
Herb species abundance	Herb_ab	0.218	0.048	¯ 0.329*	0.109
Fern species abundance	Fern_ab	0.2	0.04	0.057	0.003
Ellenberg - light	Light	¯ 0.52**	0.27	¯ 0.506**	0.256
Ellenberg - wetness	Wetness	¯ 0.438**	0.192	¯ 0.606**	0.368
Ellenberg - fertility	Fertil	0.354*	0.125	¯ 0.16	0.026
Ellenberg - competitors	Compets	0.618**	0.381	0.226	0.051
Grime's - stress tolerators	StressTo	¯ 0.174	0.03	0.312*	0.098
Grime's - ruderals	Ruderals	¯ 0.478**	0.228	¯ 0.796**	0.634
Species 'A' abundance	A_abun	0.231	0.054	0.151	0.023
Species 'B' abundance	B_abun	0.362*	0.131	0.154	0.024
Species 'A + B' abundance	A+B_abun	0.359*	0.129	0.172	0.03
Negative 1 species abundance	neg1abun	¯ 0.391**	0.153	¯ 0.566**	0.321
Negative 2 species abundance	neg2abun	0.617**	0.381	0.547**	0.3
Species richness	SppRich	0.542**	0.294	¯ 0.098	0.01
Species per square metre	Spp_sqm	0.281	0.079	0.398**	0.159
Mean emergent height	meanEm	0.762**	0.58	0.456**	0.208
Emergent - sd	sdEm	0.257	0.066	0.14	0.02
Variability in emergent type	VariEm	¯ 0.321*	0.103	¯ 0.126	0.016

Factors strongly influencing Axis 2 scores, both negatively and positively, are again tree and shrub abundance, with Ellenberg's light and wetness scores, Grime's ruderals, and negative 1 species abundance (includes Thistle, Nettle, Dock and Ragwort).

The strength and direction of the associations of these variables in relation to the limestone pavement groups can be seen in Figure 5-7 by the length and direction of the vectors. From the position of these vectors, Group 7 can be seen to be associated with high levels of negative 1 species which also corresponds to Grime's ruderals scores. Other correlations with this group include Ellenberg's light and wetness indicators and abundance of rush species found on the limestone pavements in Group 7.

Predictably, correlations with the wooded groups (Groups 4 and 8) are the abundance of tree and shrub species and mean emergent height. Negative 2 species abundance showed a positive correlation with Groups 3 and 8, with Grime's competitors correlated strongly with Group 4. A weaker, but still significant relationship with Axis 1 scores was also identified between species richness and both Group 4 and Group 6.

5.6 Secondary Analysis using the LIS

In order to make a detailed, comparable assessment of each limestone pavement, a Line Intercept Sample (LIS) was positioned uniformly at the centre of each pavement in a perpendicular orientation to the pavement's main grike direction. Detailed recordings were made regarding the geomorphology and the quantity, position and nature of the vegetation over the 10m length. Results have been presented in this chapter by their holistic classification to allow contrasts to be made between the groupings.

5.6.1 Geomorphology across the LIS

The geomorphology across the LIS was initially analysed using a ternary diagrammatic approach which is presented in Figure 5-8. The limestone pavements are coded according to their group membership. The clustering amongst the limestone pavement groups is not clearly defined in this analysis, though Groups 1 and 6 display some degree of clustering where there is a greater proportion of solution features and clint, and a lower percentage of grike across their LIS. Group 7 are loosely grouped around the area where there is a higher percentage of grike to solution features or clint.

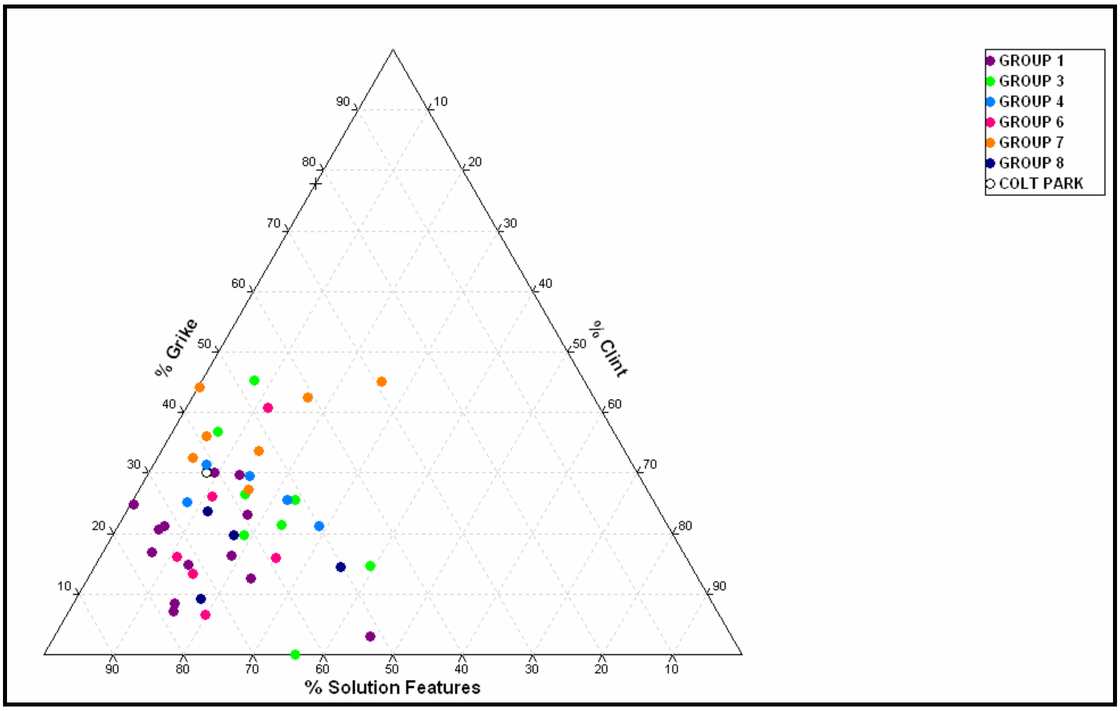

Figure 5-8: Ternary diagram showing 43 limestone pavements in their group classification and Colt Park Wood (see legend). Each limestone pavement is positioned on the chart in relation to the axis scores for % grike, % solution features and % clint across the 10m LIS.

Analysis of LIS geomorphology data using the Kruskal-Wallis test identified significant differences between groups in both the total percentage of the LIS that was grike (K-Wallis, H=17.11, df=5, p<0.01), and in the total percentage of the LIS that comprised clint/broken clint tops (K-Wallis, H=15.48, df=5, p<0.01). A Mann Whitney 'U' test concluded that all groups were significantly different from Group 7 (p<0.05), which had the highest total percentage of the LIS that was grike (mean 37.3%, +/-6.8%). Group 8 had the lowest grike percentage of all the groups (mean 16.8%, +/-6.3%).

Group 1 had the greatest percentage of clint/broken clint tops across the LIS (mean 67.7%, +/-8.6%), and Mann Whitney 'U' test revealed that it had statistically significantly more than Groups 7, 3 and 4 (U=9.5, 12.5 and 12 respectively, p<0.05). Group 7 had the lowest percentage of clint/broken clint tops (mean 50.9%, +/-11.8%), significantly less than both Group 1 and Group 6 (p<0.05).

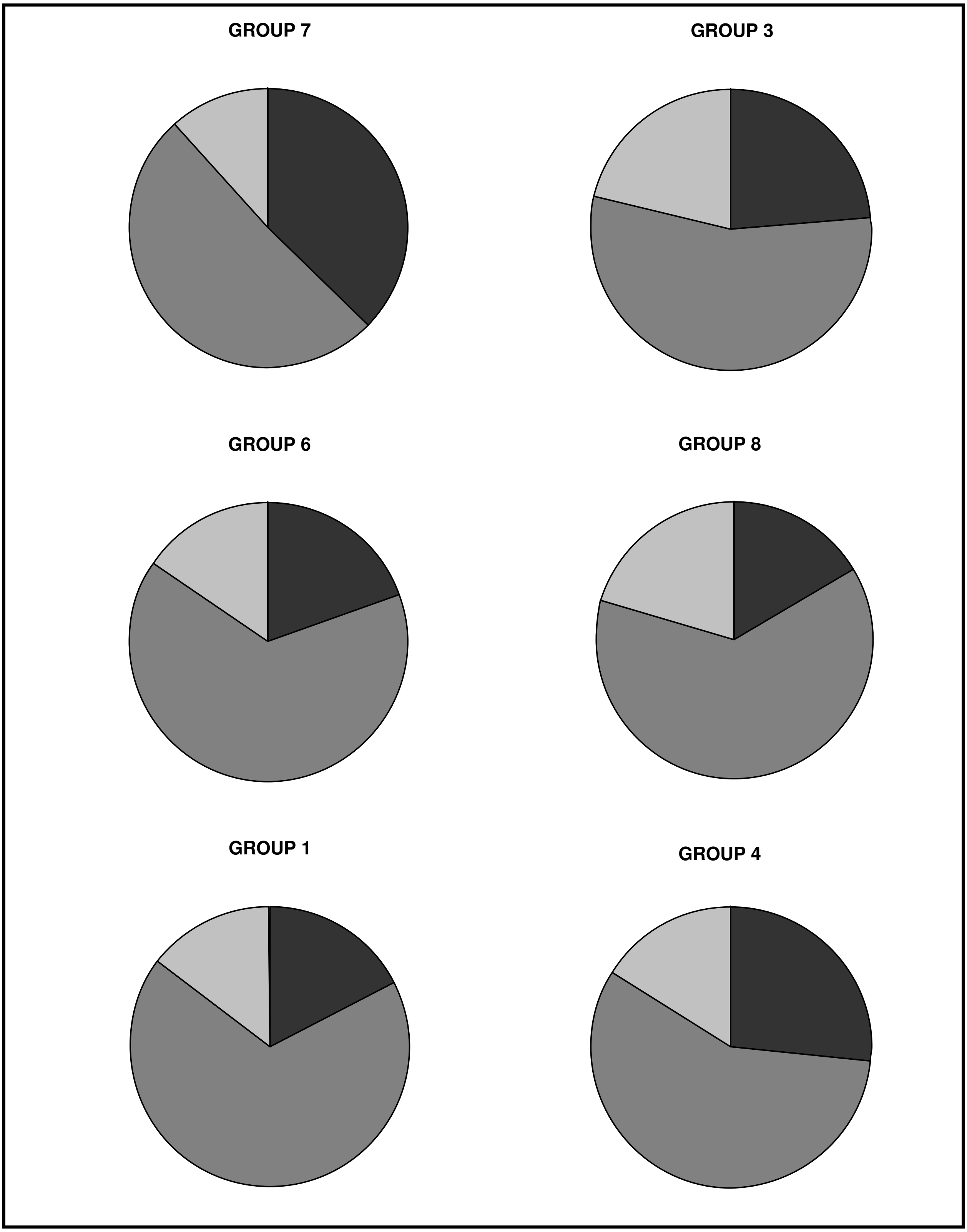

Figure 5-9: Summary of the geomorphology on the 10m LIS, by group, where ■ is total % of grike; ■ is total % of clint/broken clint and ■ is total % of solution features (including runnels).

These analyses are summarised in Figure 5-9, illustrating the greater percentage of grike on the LIS found on Group 7 limestone pavements.

Group 8 limestone pavements were found to have the smallest percentage of grike on the LIS. This corresponds to the results of the analysis of limestone pavement grike width and width standard deviation where Group 8 was found to have the narrowest grike width and least variability around this mean.

5.6.2 Vegetation Distribution across the LIS

Again, a ternary diagram was used to explore the relationship between the groups in their vegetation distribution across the transect line and this is presented in Figure 5-10. Axes were divided between grike, solution features and clint vegetation and included mosses, grasses and herbs. Limestone pavements were coded according to their group membership.

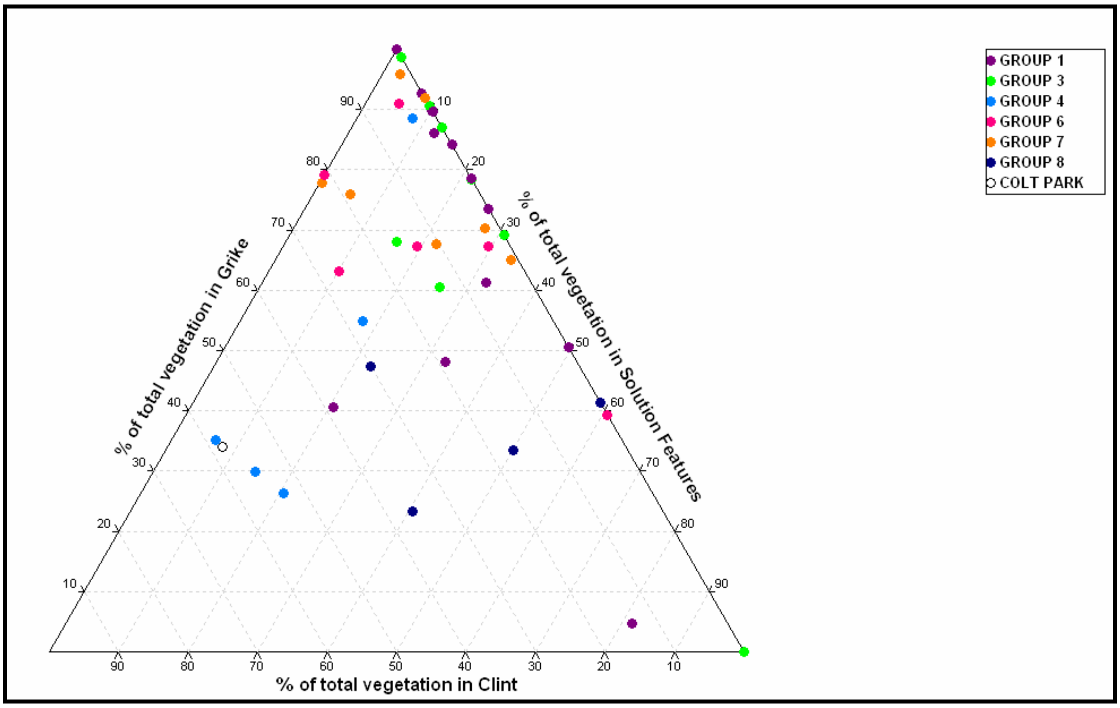

Figure 5-10: Ternary diagram of location of vegetation across the LIS, divided between grike, solution features and clint tops. Each symbol represents an individual limestone pavement, coded by group membership (see legend).

Groups 4 and 8, the wooded groups, along with Colt Park Wood, show a tendency to clustering towards higher levels of vegetation on their clints, as would be expected. Kruskal-Wallis tests of vegetation distribution on the LIS found significant differences between groups in the total percentage of vegetation on the LIS (K-Wallis, H=20.95, df=5, $p<0.01$), the percentage of vegetation present in the grikes (K-Wallis, H=10.78, df=5, $p<0.05$) and the percentage of vegetation found on the clints (K-Wallis, H=15.59, df=5, $p<0.01$). There was no significant difference between groups in the percentage of vegetation that was located in their solution features (includes runnels and solution pans). The quantity and distribution of vegetation on individual pavements across the transect is further illustrated in Figure 5-11, with a summary presented in Figure 5-12 of the distribution by group between grike, solution features and clint.

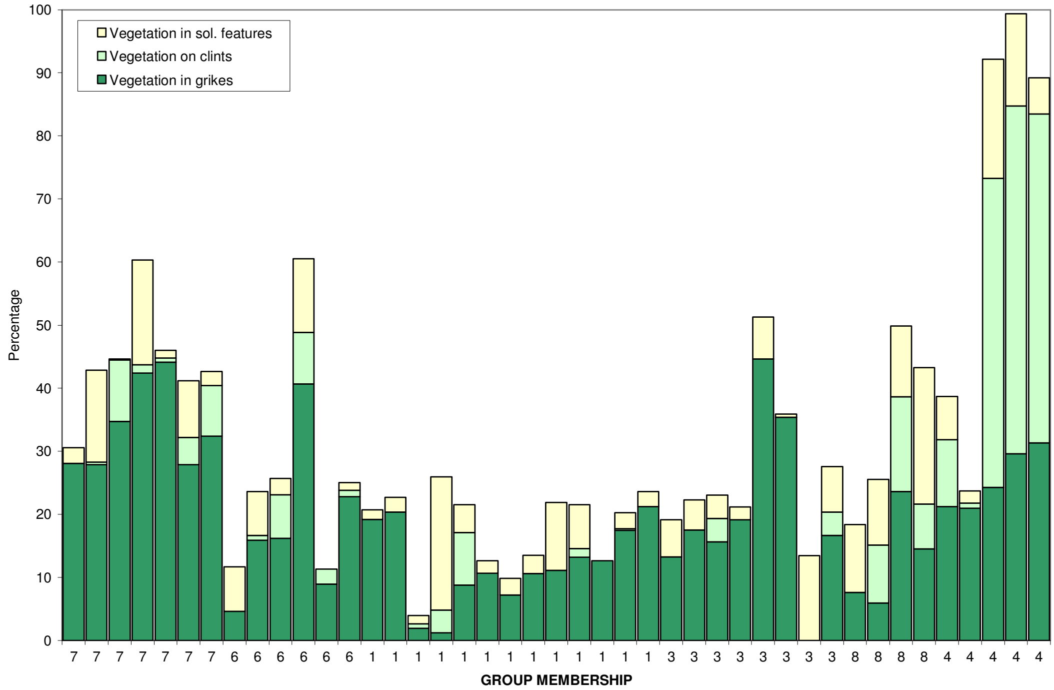

Figure 5-11: Total quantity and location of the pavement vegetation on the ten metre LIS with the 43 limestone pavements ordered by their holistic grouping.

Mann Whitney 'U' test revealed that both Group 4 and Group 7 had a significantly greater total percentage of vegetation present (mean 68.6%, +/-34.8% and 44%, +/-8.8%, respectively) across the transect line than Groups 1, 6 and 3 ($p<0.05$). Group 1 had only a group mean of 17.7%, +/-6.5% total vegetation across the LIS.

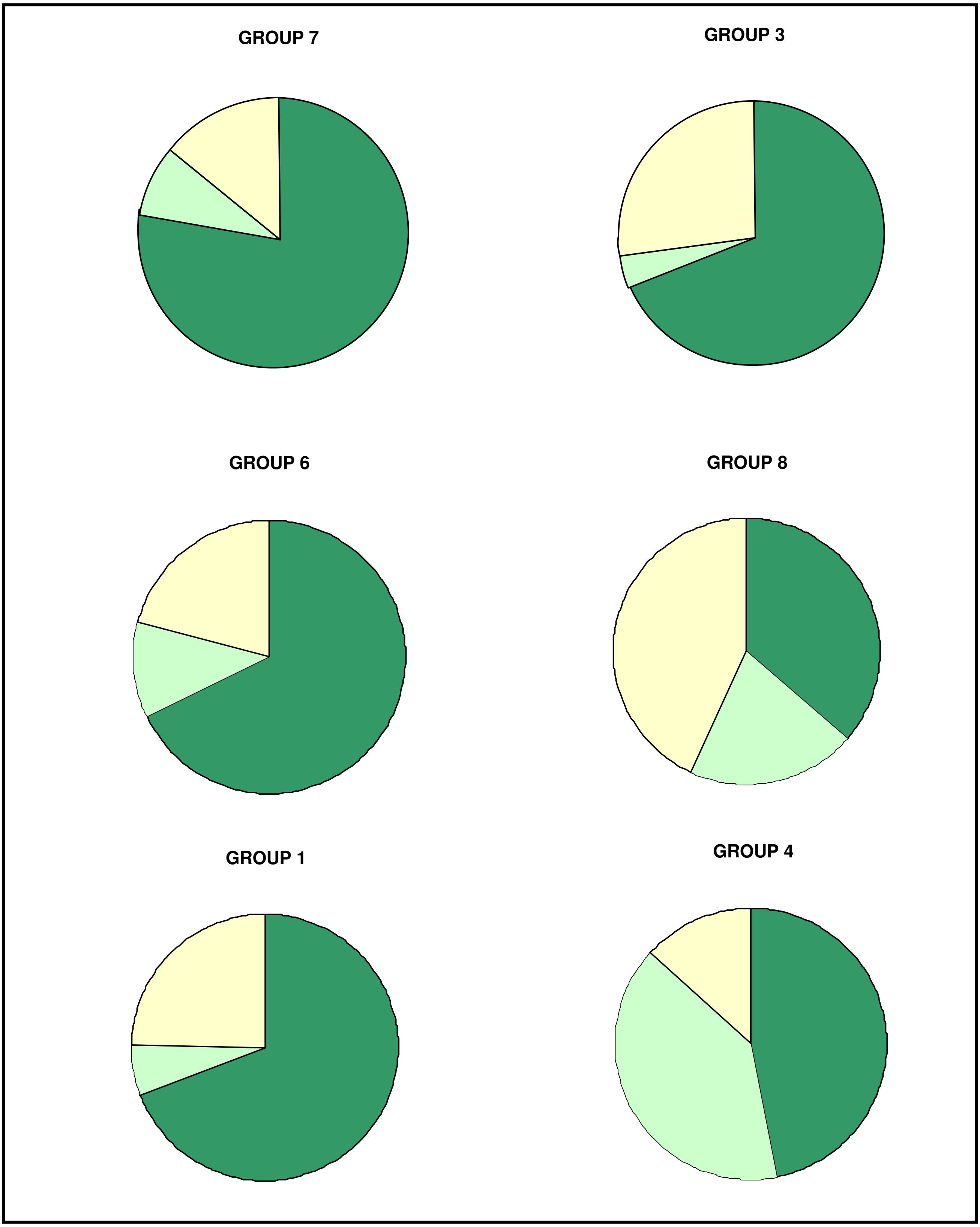

Figure 5-12: Summary of the distribution of the vegetation on the 10m LIS, by group, where ■ is % of total vegetation in the grikes; ■ is % of total vegetation on the clints and ■ is % of total vegetation in the solution features.

The greatest percentage of Group 7's vegetation was located in the wide grikes (mean 77.8%, +/-11.9%), a significantly higher percentage than Groups 8 and 4. Group 8 had the lowest mean percentage of vegetation found in the grikes with 36.4%, +/-10.4, significantly lower than Groups 3, 1 and 6 ($p<0.05$).

Group 3 had the lowest percentage of its vegetation on the clints, with a group mean of 3.7%, +/-6.9%, significantly lower than Groups 4 and 8 ($p<0.05$). Group 4 had most vegetated clints, with a group mean of 39.6%, +/-23.7% of the clints covered in vegetation, a significantly higher percentage than Groups 3, 1, 7 and 6 ($p<0.05$). The other wooded limestone pavement group, Group 8, had 20.6% (+/-16%) of its clint tops vegetated.

5.7 Descriptions of the Holistic Classification

A colour-coded summary comparison of the groups is shown in Table 5-7, grading group means and medians from high to low against measured variables. The summarised data is then presented by group, in Figure 5-13.

Particularly striking differences can be seen between the two Yorkshire limestone pavement classes, Groups 6 and 7, in relation to their grike depth, clint metrics, runnel metrics, and species richness, including A+B species presence. Group 6 has deep grikes, large clints and long, wide runnels and is the most species-rich limestone pavement group with the highest number of rare species. Conversely, Group 7 has the widest, shallowest grikes, smallest clints, fewest runnels and is the most species-poor of the limestone pavement groups. Group 1, which contains the remaining Yorkshire open limestone pavements and the Cumbrian pavements, appears to be a heterogeneous classification which lacks the distinctive characteristics of both Group 6 and Group 7.

Groups 4, 8 and 3 are primarily lowland limestone pavement groups and are divided into two wooded groups, one of which, Group 4, contains two Yorkshire wooded limestone pavements. Group 3, is an open group which has a strong maritime influence. The following descriptions aim to outline the key differences established between the six holistic functional limestone pavement classes.

Table 5-7: Graded comparison of group means and medians in relation to both geodiversity and biodiversity variables. Statistically significant differences between groups identified by ANOVA or Kruskal-Wallis are denoted * (p<0.05).

Variable	← HIGH					LOW →
Proximity to Fault*	GROUP 4	GROUP 3	GROUP 8	GROUP 1	GROUP 6	GROUP 7
Dip*	GROUP 4	GROUP 8	GROUP 3	GROUP 7	GROUP 1	GROUP 6
Altitude*	GROUP 7	GROUP 6	GROUP 1	GROUP 3	GROUP 4	GROUP 8
Slope*	GROUP 4	GROUP 8	GROUP 3	GROUP 1	GROUP 6	GROUP 7
Proximity to Coast*	GROUP 8	GROUP 3	GROUP 4	GROUP 1	GROUP 6	GROUP 7
Precipitation*	GROUP 6	GROUP 7	GROUP 1	GROUP 4	GROUP 8	GROUP 3
Days Frost*	GROUP 6	GROUP 7	GROUP 1	GROUP 4	GROUP 3	GROUP 8
Windspeed	GROUP 7	GROUP 3	GROUP 1	GROUP 4	GROUP 8	GROUP 6
Pavement Area	GROUP 7	GROUP 6	GROUP 1	GROUP 4	GROUP 3	GROUP 8
Grike Depth	GROUP 8	GROUP 6	GROUP 4	GROUP 3	GROUP 1	GROUP 7
Grike Depth (sd)*	GROUP 7	GROUP 1	GROUP 3	GROUP 4	GROUP 6	GROUP 8
Grike Width	GROUP 7	GROUP 6	GROUP 4	GROUP 3	GROUP 1	GROUP 8
Grike Width (sd)	GROUP 7	GROUP 6	GROUP 4	GROUP 3	GROUP 1	GROUP 8
Clint Width	GROUP 6	GROUP 3	GROUP 8	GROUP 1	GROUP 4	GROUP 7
Clint Width (sd) - rank*	GROUP 6	GROUP 3	GROUP 8	GROUP 4	GROUP 1	GROUP 7
Clint Length	GROUP 6	GROUP 3	GROUP 8	GROUP 4	GROUP 1	GROUP 7
Clint Length (sd)	GROUP 6	GROUP 4	GROUP 3	GROUP 8	GROUP 1	GROUP 7
Clint Perimeter	GROUP 6	GROUP 3	GROUP 8	GROUP 4	GROUP 1	GROUP 7
Clint Perimeter (sd)	GROUP 6	GROUP 8	GROUP 4	GROUP 3	GROUP 1	GROUP 7
Clint Frequency	GROUP 7	GROUP 4	GROUP 1	GROUP 8	GROUP 3	GROUP 6
Runnel Width	GROUP 6	GROUP 3	GROUP 7	GROUP 1	GROUP 4	GROUP 8
Runnel Width (sd)	GROUP 7	GROUP 3	GROUP 6	GROUP 1	GROUP 4	GROUP 8
Runnel Length	GROUP 8	GROUP 6	GROUP 3	GROUP 1	GROUP 4	GROUP 7
Runnel Length (sd)	GROUP 8	GROUP 6	GROUP 3	GROUP 1	GROUP 4	GROUP 7
Runnel Frequency	GROUP 4	GROUP 8	GROUP 3	GROUP 6	GROUP 1	GROUP 7
MV Frequency	GROUP 8	GROUP 3	GROUP 1	GROUP 6	GROUP 7	GROUP 4
Soil Depth	GROUP 7	GROUP 6	GROUP 4	GROUP 1	GROUP 3	GROUP 8
Emergent Height*	GROUP 4	GROUP 8	GROUP 3	GROUP 6	GROUP 1	GROUP 7
Sward Height*	GROUP 8	GROUP 4	GROUP 3	GROUP 1	GROUP 6	GROUP 7
Species Richness*	GROUP 6	GROUP 4	GROUP 3	GROUP 8	GROUP 1	GROUP 7
AB (Rare) Species*	GROUP 6	GROUP 8	GROUP 3	GROUP 1	GROUP 4	GROUP 7
Negative1 Species*	GROUP 6	GROUP 1	GROUP 3	GROUP 7	GROUP 4	GROUP 8
Negative2 Species - rank*	GROUP 3	GROUP 8	GROUP 4	GROUP 6	GROUP 1	GROUP 7
No. Tree Species*	GROUP 8	GROUP 4	GROUP 3	GROUP 6	GROUP 1	GROUP 7
No. Shrub Species - rank*	GROUP 8	GROUP 4	GROUP 3	GROUP 6	GROUP 1	GROUP 7
No. Moss Species*	GROUP 4	GROUP 6	GROUP 1	GROUP 7	GROUP 8	GROUP 3
No. Herb Species*	GROUP 6	GROUP 3	GROUP 4	GROUP 1	GROUP 7	GROUP 8
No. Fern Species*	GROUP 1	GROUP 6	GROUP 4	GROUP 3	GROUP 8	GROUP 7
No. Grass Species	GROUP 6	GROUP 4	GROUP 3	GROUP 8	GROUP 1	GROUP 7
No. Rush Species - rank*	GROUP 7	GROUP 6	GROUP 1			
No. Sedge Species	GROUP 8	GROUP 6	GROUP 4	GROUP 3	GROUP 1	GROUP 7
Ellenberg - Light*	GROUP 7	GROUP 6	GROUP 8	GROUP 1	GROUP 3	GROUP 4
Ellenberg - Wetness*	GROUP 7	GROUP 6	GROUP 1	GROUP 4	GROUP 8	GROUP 3
Ellenberg - Fertility*	GROUP 6	GROUP 4	GROUP 1	GROUP 3	GROUP 8	GROUP 7
Ellenberg - pH*	GROUP 6	GROUP 1	GROUP 3	GROUP 4	GROUP 8	GROUP 7
Grime’s - Competitors*	GROUP 6	GROUP 8	GROUP 4	GROUP 3	GROUP 1	GROUP 7
Grime's - Stress Tolerators	GROUP 8	GROUP 7	GROUP 3	GROUP 4	GROUP 1	GROUP 6
Grime’s - Ruderals*	GROUP 6	GROUP 7	GROUP 1	GROUP 4	GROUP 3	GROUP 8

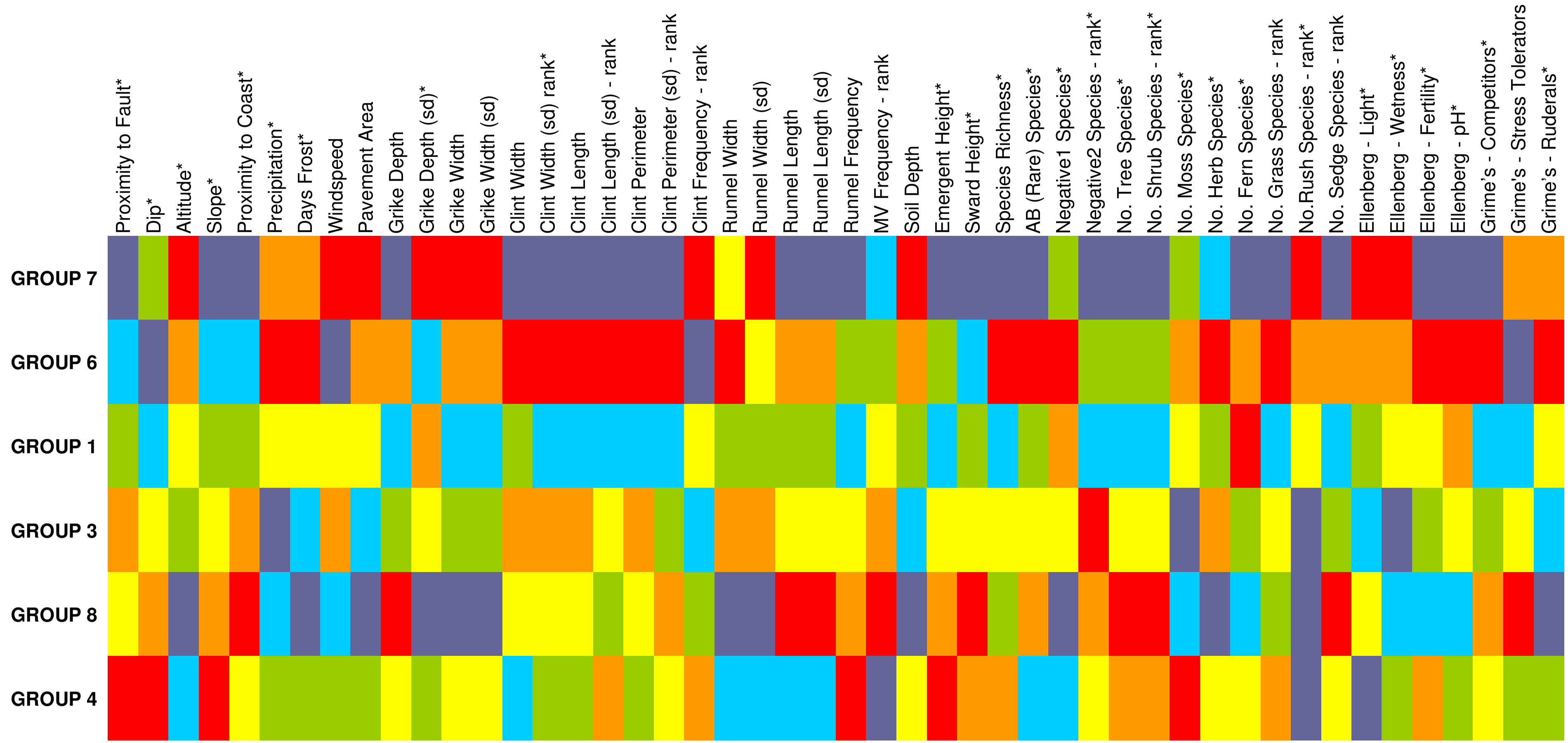

Figure 5-13: Grading of group means and medians by each limestone pavement classification, with * denoting statistically significant differences between groups identified by ANOVA or Kruskal-Wallis (p<0.05). Variations in colour coding correspond to mean/median scores where:

■ = very high; ■ = high; ■ = medium high; ■ = medium; ■ = medium low; and ■ = low.

Plant indicator species analysis (Dufrene & Legendre, 1997) was conducted on species presence/absence data using the limestone pavement groups in PC-ORD (McCune & Mefford, 2006). This analysis combined information on the proportional abundance of a particular species in each group with the faithfulness of its occurrence in that group. A perfect indicator species would be present on each limestone pavement in the group, and would occur exclusively in that group, scoring an ‘observed indicator value (IV)’ of 100 (McCune & Grace, 2002). Comparison of the observed score with randomly produced scores in PC-ORD gives the statistical significance of each indicator value. The significant indicator values ($p<0.05$) are tabulated under the six group descriptions in the following sections. In Section 5.8 the distinctions between the six groups are then summarised graphically and field guides to the classification are presented.

5.7.1 Group 7 - A higher altitude limestone pavement group with shallow, wide grikes, typically heavily grazed

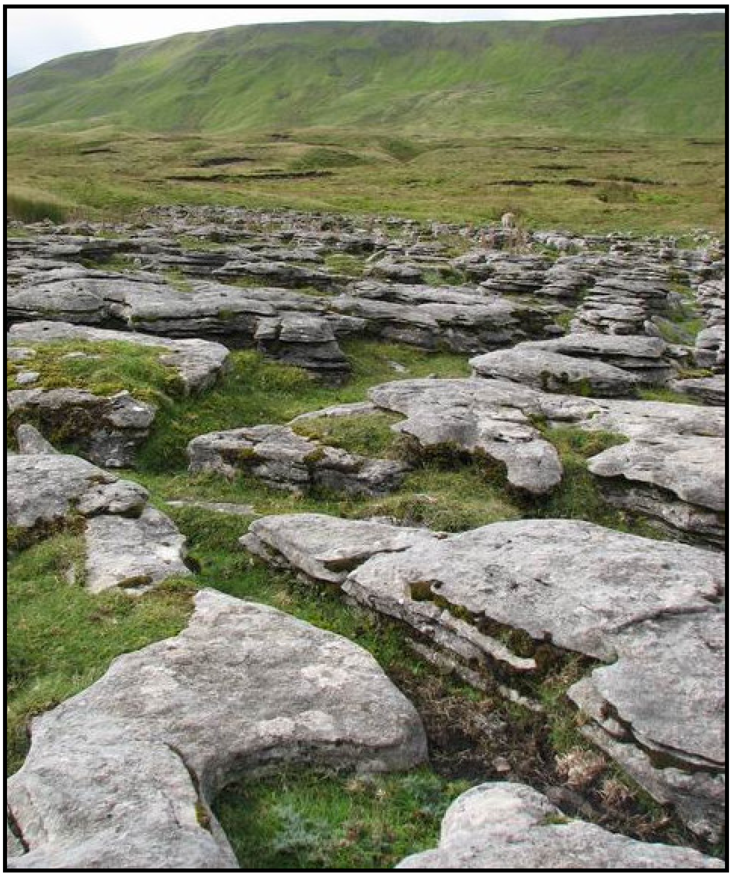

Figure 5-14: Greensett limestone pavement, Whernside, in Group 7. Bedding planes are thin and the layering can be clearly seen where the pavement has weathered at different rates as it has been exposed to the elements.

Table 5-8: Limestone pavements in Group 7 included the following:

Pavement name	Study code	Ward & Evans unit	Grid ref
Bordley	MACBOR	Malham-Arncliffe stand 34	SD954648
Langcliffe	MACLAN	Conistone stand OA	SD983721
Lea Green	MACLG	Conistone stand 21	SD997662
Cam High Road	YORCAM	Yoredale Series stand 6	SD854840
Greensett	YORGR	Yoredale Series stand 1	SD747821
Rocky Ground	YORRG	Yoredale Series stand 1	SD863735
Wold Fell	YORWF	Yoredale Series stand 1	SD791850

Table 5-9: Plant species with significant indicators values in Group 7.

Group 7 Indicator Species	Observed Indicator Value (IV)	IV from randomised groups		p value
		Mean	s.d.	
Oxalis acetosella	23.2	20.3	1.77	0.001
Luzula campestris	44.2	14.1	8.13	0.007
Rhytidiadelphus squarrosus	39.5	15.8	7.26	0.015
Cirsium palustre	37.3	16.5	7.43	0.019
Trifolium spp.	37.8	14.5	7.97	0.019
Achillea millefolium	33.3	14.9	7.72	0.028
Climacium dendroides	32.1	15.3	7.34	0.032
Agrostis spp.	29.7	15.3	7.64	0.048
Prunella vulgaris	29.9	15.3	7.53	0.050

This limestone pavement group comprises the majority of the limestone pavements from the Yoredale Group, excepting Hawkswick Clowder, with three pavements in the Malham-Arncliffe area (Table 5-8). Rocky Ground was a borderline member of this group on the TWINSPAN analysis.

These limestone pavements had the thinnest beds, were generally level and were the most distant of all the groups from major structural influence. This classification had the richest palaeontology, with frequent to abundant macrofossils present at three of the seven limestone pavements; Langcliffe, Cam High Road (Figure 5-14) and Greensett, including unbroken Brachiopods, Crinoids and Corals. This illustrates an original rich biodiversity on clear undisturbed substrate during the period of deposition.

Group 7 was very exposed, being at the highest mean altitude (458.57m, +/-116.43m) and subject to the greatest mean annual windspeed (6.34m/s, +/-2.02m/s). This group had the shallowest mean grike depth of all the limestone pavements (0.48m, +/-0.37m), due probably to the bed thickness. It had the widest grikes (mean 0.28m, +/-0.09m) with the highest percentage of grike across the 10m LIS. Mean clint size was the smallest across all dimensions (width, length and perimeter) and clint frequency was the highest of all limestone pavement groups. Runnel frequency was the lowest and mean runnel length the smallest at 292.9mm, +/-76.2mm. The modal subjective quality assessment score of the geomorphology of these limestone pavements was 3/5, the lowest geomorphology quality rating of the groups.

Group 7 had the largest mean pavement area, but the lowest species richness and the least presence of limestone pavement specialist species. Emergent height was the lowest (mean 1.02m, +/-1.3m) and these pavements had the shortest sward. All limestone pavements in this group had medium to high levels of grazing by both sheep and rabbits. Soil depth in the grikes was the deepest of the limestone groups at 217.4mm, +/-70.2mm.

Species composition on Group 7 limestone pavements lacked trees, shrubs and ferns. Plant indicator species are detailed in Table 5-9 and include mosses, a grass and a rush species, all generally associated with moist, neutral to acidic grassland (Hill *et al.*, 1999).

5.7.2 <u>Group 6 - A higher altitude, level, species-rich, thickly-bedded open limestone pavement group</u>

Figure 5-15: Scar Close, Ingleborough (Group 6) displaying thick limestone beds, deep grikes and large un-dissected clints. This limestone pavement was the most species-rich limestone pavement in both Group 6 and the entire study, with 13 limestone pavement specialist species present. Grazing has been excluded from this site since 1960 (Waltham *et al.*, 1997).

Table 5-10: Limestone pavements in Group 6 included the following:

Pavement name	Study code	Ward & Evans unit	Grid ref
Scar Close	IBSCAR	Ingleborough stand 29	SD748771
Top Cow	IBTC	Ingleborough stand 29	SD782759
Dale Head	KWPDH	Pen-y-Ghent stand 8	SD840714
Old Ing	KWPOLD	Pen-y-Ghent stand 1	SD782774
Malham Cove	MACMC	Malham-Arncliffe stand 37	SD897641
Tennant Gill	MACTG	Malham-Arncliffe stand 3	SD881694

Table 5-11: Plant species with significant indicators values in Group 6. Limestone pavement specialist species are emboldened.

Group 6 Indicator Species	Observed Indicator Value (IV)	IV from randomised groups		p value
		Mean	s.d.	
Anthoxanthum odoratum	69	15.9	7.35	0.000
Cirsium arvense - neg1 spp	39.9	19.6	5.13	0.000
Stachys sylvatica	65.9	16.8	6.97	0.000
Vicia sepium	83.3	14.1	7.98	0.000
Geranium lucidum	83.3	14.2	8.09	0.000
Heracleum sphondylium	52.1	17.7	6.73	0.000
Rumex acetosa	50	13.2	7.55	0.002
Arrhenatherum elatius	51.1	15.4	7.55	0.003
Silene dioica	54.9	14.2	7.89	0.003
Erophila verna	50	13.2	7.67	0.003
Ribes spicatum - 'A' spp	**50**	**13.4**	**8.03**	**0.004**
Filipendula ulmaria	37.7	16.7	6.96	0.012
Primula vulgaris	36.2	17.1	6.99	0.015
Scrophularia nodosa	38.2	13.9	8.07	0.017
Ditrichum gracile	35.1	18	6.57	0.021
Cardamine pratensis	37.9	15.6	7.63	0.023
Dryopteris dilitata	35.1	15	7.78	0.023
Hypochaeris radicata	33.3	13.4	6.65	0.032
Actaea spicata - 'A' spp.	**33.3**	**13.7**	**6.89**	**0.035**
Cruciata laevipes	33.3	13.7	6.86	0.036
Ranunculus acris	33.3	13.6	6.81	0.036
Valeriana officinalis	33.2	15.9	7.06	0.036
Trollius europaeus	33.3	13.6	6.95	0.038
Campanula rotundifolia	30.6	18.4	6.07	0.039
Veronica chamaedrys	29.7	14	7.88	0.041

Group 6 comprised six members (Table 5-10) and collectively they displayed the highest quality features of the four open limestone pavement holistic classes, for both geodiversity and biodiversity. These pavements were level, with modal limestone bed depth in the range 2-2.49m, thickest of the groups, all on the Danny Bridge Formation, Great Scar Limestone.

This group had the largest clint size (width, length and perimeter) of the groups with deep grikes averaging 0.97m, +/-0.51m, again probably directly related to bed thickness. Mean grike width was 0.25m, +/-0.15m, one of the wider groups. Group 6 had the widest runnels (mean 144.2mm, +/- 124.7mm) and they were long at 817.7mm, +/-1033.7mm. The modal subjective score for the quality of the geodiversity on these pavements was 5, the highest rating, though it should be noted that Old Ing scored only 2 for the quality of its geodiversity.

These pavements were at a mean altitude of 364.83m, +/-58.04m and had the highest estimated precipitation and frost levels of all the groups. Despite this they were the most species rich, and had the highest presence of limestone pavement specialist species, including two of these rare species as indicator species, *Ribes spicatum* (Downy currant) and *Actaea spicata* (Baneberry), see Table 5-10. *Trollius europaeus* (Globeflower), an uncommon upland species (Groom, 2010; Yorkshire Dales National Park Authority, 2010) and a positive limestone pavement species (JNCC, 1997) was also an indicator species in Group 6. However, this group also had the largest number of negative 1 species, including *Cirsium arvense* (Creeping thistle), an indicator species for Group 6, which was observed as 'rare' on Scar Close (Figure 5-15) but was 'occasional' on five of the pavements in the group and 'frequent' on Old Ing limestone pavement, suggesting less than optimal grazing management (JNCC, 1997).

Grazing was light on three of the six limestone pavements, with only Dale Head displaying heavy grazing levels, primarily from rabbits, and Old Ing and Malham Cove having medium grazing levels. Generally, even where sheep were present, the geomorphology of Group 6 limestone pavements largely precluded the sheep from accessing the grike vegetation, as clints were large and grikes deep. Analysis of the emergent species in this group identified trees (primarily Ash, *Fraxinus excelsior)* as the modal tallest species, observed on Scar Close, Top Cow and Malham Cove. However, two of the limestone pavements in this group had negative 1 species as their modal emergent species, namely Dale Head (Creeping thistle, *Cirsium arvense*) and Old Ing (Nettle, *Urtica dioica*).

5.7.3 Group 1 - A higher altitude, open limestone pavement group with mid-range grike depth 0.5-1m and low species richness

Figure 5-16: Crummack Dale limestone pavement in Group 1.

Table 5-12: Limestone pavements in Group 1 included the following:

Pavement name	Study Code	Ward & Evans unit	Grid ref
Fell End Clouds	CUCLO	The Clouds stand 5	SD737998
Great Asby Scar	CUGAS	Gt. Asby stand 44	NY657104
Royalty Allotment	CURA	Gt. Asby stand 24	NY645105
Sayle Bottom	CUSB	Gt. Asby stand 19	NY655110
Sunbiggin	CUSUN	Gt. Asby stand 58	NY646090
Clapdale Scars	IBCLAP	Ingleborough stand 73	SD749709
Crummack Dale	IBCRUM	Ingleborough stand 63	SD772719
Sulber	IBSUL	Ingleborough stand 44	SD774738
Ewe's Top	KWPEWE	Whernside stand 6	SD704758
Little Stainforth	KWPLS	Feizor stand 21	SD810662
Smearsett Copys	KWPSC	Feizor stand 5	SD799683
Hill Castles Scar	MACHCS	Conistone stand 9	SD991684
Hawkswick Clowder	YORHAW	Malham-Arncliffe stand 23	SD947687

The third Yorkshire/Cumbrian class, Group 1, showed less homogeneity than Groups 7 and 6, suggesting that this may have been a ‘bucket’ group i.e. lacking the wide, shallow grikes of Group 7 or the deep grikes of Group 6.

With 13 pavements (detailed in Table 5-12), this was the largest holistic grouping in the study.

Table 5-13: Plant species with significant indicators values in Group 1, with limestone pavement specialist species emboldened.

Group 1 Indicator Species	Observed Indicator Value (IV)	IV from randomised groups		p value
		Mean	s.d.	
Urtica dioica - neg1 spp	26.6	20.5	2.96	0.000
Asplenium viride - 'B' spp.	**31.1**	**20.3**	**4.14**	**0.000**
Cystopteris fragilis - 'B' spp.	**26.6**	**20.6**	**2.96**	**0.001**
Mercurialis perennis	20.9	19.3	0.62	0.001
Cirsium vulgare - neg1 spp	25.8	20.5	2.97	0.002
Athyrium felix-femina	42.7	17.6	6.63	0.008
Mycelis muralis - 'B' spp.	**23.2**	**20.4**	**2.2**	**0.018**

Group 1 limestone pavements were generally level and at a mean altitude of 359.62m, +/-53.17m, ranging between 274m and 450m. Their geomorphology was typically mid-range, grike depth varying between 0.51m and 0.98m (mean 0.69m, +/-0.12m), mean grike width at 0.17m, +/-0.06m, with medium sized clints and runnels.

Species richness was low, though above that of Group 7, and these pavements had statistically significantly more limestone pavement specialist species than Group 7. The species assemblage in Group 1 contained the most ferns of any of the classes, including classic limestone pavement species *Asplenium viride* (Green spleenwort) and *Cystopteris fragilis* (Brittle bladder fern). Three of the indicator species for the group were 'B' species (Table 5-13), these two ferns and *Mycelis muralis* (Wall rue), species which have a high conservation value as they are dependent on limestone pavement habitat for maintaining their populations in the UK (Ward & Evans, 1976).

Emergent height and sward height were both mid-range in Group 1, and modal grazing intensity was medium level. On nearly half of these limestone pavements, the highest emergent species (modal) was a negative 1 species, *Cirsium spp.* (Thistle) or *Urtica dioica* (Nettle), and these species feature in the indicator species for the group. An example of one of the limestone pavements in Group 1, Crummack Dale, is shown in Figure 5-16. This pavement is typical of the group, i.e. well weathered and exposed, with medium levels of sheep and rabbit grazing and *Cirsium vulgare* (Spear thistle) as the modal emergent species.

5.7.4 Group 3 - An open, coastal limestone pavement group with little moss growth and un-vegetated clints

Figure 5-17: High Farm Allotment (Group 3) overlooking Morecambe Bay.

Table 5-14: Limestone pavements in Group 3 included the following:

Pavement name	Study Code	Ward & Evans unit	Grid ref
Hutton Roof Crags	HRCRAG	Hutton Roof stand 48A	SD557776
Holme Park Fell East	HRHPE	Hutton Roof stand 13	SD547790
Holme Park West	HRHPW	Hutton Roof stand 7	SD540796
Holme Park Quarry	HRHQ	Hutton Roof stand 20	SD538788
High Farm Allotment	MBHFA	Hampsfield Fell stand 22	SD404791
Bryn Alyn	NWBA	North Wales stand 21	SJ198589
Great Orme	NWGO	North Wales stand 14	SH757839
Taranau	NWTAR	N/A	SJ182720

Group 3 comprised eight limestone pavements from Hutton Roof, Morecambe Bay and North Wales, detailed in Table 5-14. All pavements in this group were situated within 15km of the coast and five had a maritime influence, with the coast visible from the pavement stand. This group was also subject to reasonable levels of structural influence, situated on average within 1.2km of a major fault. This was reflected in the degree of pavement slope and dip. Mean limestone pavement slope was 7^o (+/-2.3^o) with dip ranging from 5^o-25^o (mean 12.5^o).

Table 5-15: Plant species with significant indicators values in Group 3, with limestone pavement specialist species emboldened.

Group 3 Indicator Species	Observed Indicator Value (IV)	IV from randomised groups		p value
		Mean	s.d.	
Ulex europaeus -neg2 spp	75	14.6	8.2	0.000
Sonchus spp.- neg1 spp	53.1	15.6	7.68	0.001
Leontodon hispidus	45.7	16.3	7.37	0.004
Pilosella officinarum	41.2	15.9	7.42	0.008
Thymus polytrichus	22	20	1.32	0.009
Inula conyzae - 'B' spp.	**33.3**	**14**	**8.25**	**0.028**
Carlina vulgaris	32.2	14.6	8.1	0.032

Group 3 experienced the lowest precipitation of all six groups and significantly less frost than Groups 7, 6 and 1, as expected due to their maritime influence. Grike width and depth was mid-range in this group, at mean values of 0.19m, +/-0.03m and 0.73m, +/-0.39m respectively. Clints were larger than the study average with this group having the second largest mean clint size. Soil depth in the grikes was one of the shallowest, measured at 120.8mm, +/-69.3mm (mean).

Species richness on Group 3 limestone pavements was at medium levels but there was the largest presence of negative 2 species recorded on these pavements. These are species that have a negative impact on other more highly valued limestone pavement species and included *Pteridium aquilinum* (Bracken) and *Ulex europaeus* (Gorse), recorded on six of the eight limestone pavements in Group 3. Bracken was notably abundant on the Hutton Roof limestone pavements, particularly on Holme Park Fell, along with Gorse, and occurred at frequent levels on Great Orme and Taranau in North Wales. Indicator species for Group 3 included one rare limestone pavement species along with Gorse and a negative 1 species, *Sonchus spp.* (Sow-thistle).

Grazing levels were lower than the Yorkshire and Cumbrian groups and sward height was greater, ranging from 20mm to 400mm, mean 196.3, +/-133.5mm. Emergent height also exceeded that of Groups 7, 6 and 1. In the analysis of the vegetation across the LIS, Group 3 limestone pavements had the lowest percentage of their vegetation on the clints, significantly less than Groups 8 and 4. This group had the lowest number of moss species recorded.

5.7.5 Group 8 - A lower altitude, sloping woodland limestone pavement group with Oak and Silver birch predominant

Figure 5-18: Bryn Pydew limestone pavement in North Wales, an example of a limestone pavement in Group 8.

Table 5-16: Limestone pavements in Group 8 include the following:

Pavement name	Study Code	Ward & Evans unit	Grid ref
Farrar's Allotment	MBFAR	Whitbarrow stands 34/35	SD451860
Gait Barrow's Wood	MBGB	Morecambe Bay E. stand 17	SD479772
Underlaid Wood	MBUW	N/A	SD485790
Bryn Pydew	NWBP	North Wales stand 16	SH817798

Group 8 limestone pavements had the lowest mean altitude at 86.75m, +/- 61.88m and the closest proximity to the coast, comprising just four limestone pavements (Table 5-16), three wooded Morecambe Bay pavements and Bryn Pydew near Llandudno, North Wales (Figure 5-18). This group also had a moderating climatic influence from the coastal proximity, with the fewest days of ground frost and the second lowest precipitation levels.

Table 5-17: Plant species with significant indicators values in Group 8, with limestone pavement specialist species emboldened.

Group 8 Indicator Species	Observed Indicator Value (IV)	IV from randomised groups		p value
		Mean	s.d.	
Betula pendula	59.2	13.3	7.72	0.001
Quercus spp.	59.2	13.6	8.01	0.002
***Taxus baccata* - 'B' spp.**	**43.4**	**17.2**	**6.6**	**0.005**
Thuja plicata - neg2 spp.	50	13.4	6.54	0.006
Polypodium australe	50	13.6	6.68	0.007
***Juniperus communis* - 'B' spp.**	**38.8**	**15.5**	**7.6**	**0.019**
Prunus spinosa	34.2	18.3	6.06	0.025
Helictotrichon pubescens	37.5	13.2	7.74	0.026
Solidago virgaurea	33.3	13.4	7.85	0.033
Sorbus aria	33.3	13.6	8	0.034
Centaurea nigra	34.6	15.9	7.32	0.035
Lonicera periclymenum	33	16.2	7.06	0.039

The quality of the geomorphology in Group 8 was ranked as high on all four limestone pavements. Grike depth was the deepest of all the groups at 1.11m, +/-0.48m (mean) and they also had the narrowest grikes at 0.16m, +/-0.04m (mean). With pavement dip ranging from 10-22^{o} (mean 14.5^{o}, +/- 5.7^{o}), runnel frequency was high, and runnels were the longest and narrowest of all the groups (means 896.8mm, +/-646.2mm and 78.8mm, +/-18.5mm, respectively). Mean soil depth in the grikes of the limestone pavements in Group 8 was the shallowest at 114.2mm, +/-33.1mm. The highest degree of mineral vein intrusion was also noted on these pavements.

Despite having the smallest pavement area (15,868 sq.m.), this group had the greatest number of tree and shrub species, with the lowest number of herbs. These pavements were the richest for sedge species and showed the highest score for stress tolerators (after Grime, 1988). The higher presence of species that are able to withstand constraints such as periods of drought or low nutrient levels is indicative of undisturbed, well established habitats (Grime, 2002). Woodland habitats generally demonstrate more stable microclimates due to lack of disturbance and presence of trees and CSR scores from Group 8 plant analysis reflect this (Figure 5-6) (Hodgson *et al.*, 1999). Group 8 had the lowest ruderals score again suggesting disturbance is low, the highest sward of all the groups, and virtually no grazing. Indicator species were primarily tree and shrub species including two 'B' species, *Juniperus communis* (Juniper), a scrub species with high conservation value

(Mortimer *et al.*, 2000), and *Taxus baccata* (Yew), but also include *Thuja plicata* (Western Red Cedar), a negative 2 species (Table 5-17).

On the LIS, Group 8 had the lowest percentage of grike, lowest percentage of vegetation in the grikes and correspondingly a high percentage of vegetation on the clints at 20.6%, significantly greater than Group 3.

Analysis of this group using the MAVIS computer programme (Centre for Ecology and Hydrology, 2000) resulted in a homologous score of vegetation class 35 for all four limestone pavements in Group 8, corresponding to 'Diverse base rich woodland/hedges' under the Countryside Vegetation Scheme (CVS) (Bunce *et al.*, 1999). This class mainly occurs in the lowlands of southern Britain, especially in the West Country, but it extends to the marginal uplands and to some northern lowlands (Bunce *et al.*, 1999) and is most similar to NVC category W8 - 'Lowland mixed broadleaved woodland with dog's mercury' (Rodwell, 1991).

5.7.6 Group 4 - A mossy, densely vegetated woodland limestone pavement group

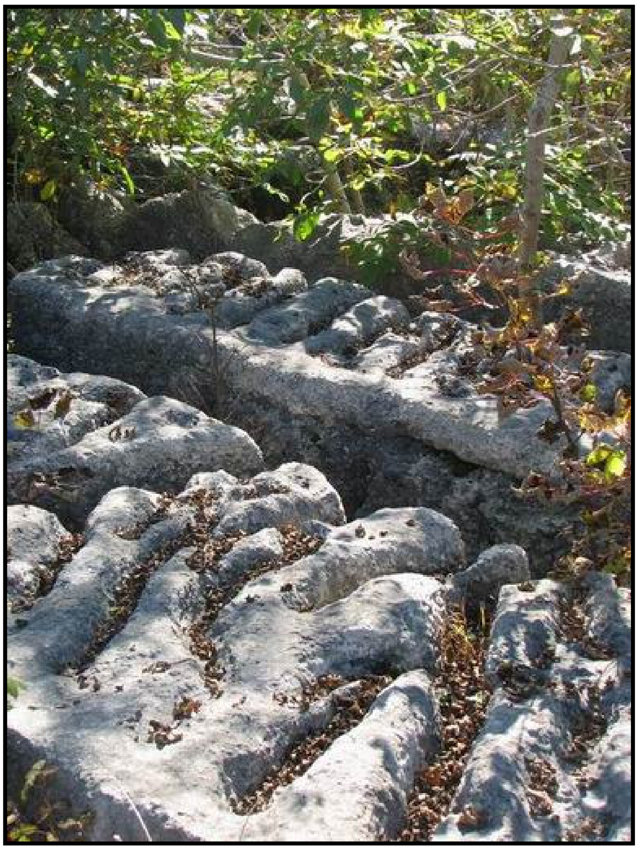

Figure 5-19: Frequent runnels at Dalton Crags, Hutton Roof, in Group 4.

Table 5-18: Limestone pavements in Group 4 included the following:

Pavement name	Study Code	Ward & Evans unit	Grid ref
Dalton Crags	HRDAL	Hutton Roof stand 48A	SD552770
Oxenber Wood	KWPOX	Feizor stand 1	SD781683
Bastow Wood	MACBW	Conistone stands 25a/25b	SD994654
Hampsfield Wood	MBHW	N/A	SD402805
Trowbarrow Quarry	MBTQ	N/A	SD481761

Table 5-19: Plant species with significant indicators values in Group 4, with limestone pavement specialist species emboldened.

Group 4 Indicator Species	Observed Indicator Value (IV)	IV from randomised groups		p value
		Mean	s.d.	
Rhamnus cathartica -'B' spp.	**51.1**	**14.8**	**7.52**	**0.002**
Dicranum scoparium	49.3	15.8	7.43	0.004
Thamnobryum spp.	41.6	18.3	6.4	0.005
Thuidium tamariscinum	41.8	16.2	7.06	0.006
Atrichum undulatum	40	13.5	6.46	0.017
Neckera complanata	40	13.5	6.79	0.018
Ilex aquifolium	35	18.6	5.93	0.028
Mnium hornum	34.9	15.5	7.52	0.029
Geum urbanum	32.7	14.4	8.02	0.031
Larix decidua	33.5	13	7.57	0.037
Rubus fruticosus	31.2	18.6	5.83	0.039
Orchis mascula	31	14.7	8.43	0.041
Rosa canina	32.3	19	5.7	0.046
Tamus communis	30.5	13.2	7.83	0.048
Teucrium scorodonia	29.2	19.2	5.45	0.065

Group 4 was the only group combining the higher altitude Yorkshire limestone pavements with pavements from Morecambe Bay and Hutton Roof (Table 5-18). These limestone pavements had the largest structural influence of all the groups, situated on average within 1km of a major fault. They had the greatest degree of slope of all the classes and generally had a dip of 10^{o}-13^{o} with Trowbarrow Quarry, Silverdale, ranging up to a 40^{o} dip (group mean 17.4^{o}, +/-12.7^{o}), highest of all the groups. Runnel frequency was highest in Group 4, illustrated in Figure 5-19, with a mean average 1.94 runnels (+/-1.68) per metre of limestone pavement.

The characteristics of the plant communities on Group 4 limestone pavements were that they had high numbers of tree and moss species with few negative 1 species. This group had the greatest number of moss species of all the groups, and statistically significantly more than Groups 3 and 8, the other lower altitude limestone pavement classes (mean 13.2 species, +/-5.1

species). Ellenberg's light indicator score (Hill *et al.*, 1999) was lowest for this limestone pavement group (Figure 5-6).

Group 4 indicator plant species are detailed in Table 5-19 and included six moss species, most significantly *Dicranum scoparium* and *Thamnobryum spp.* *Rhamnus cathartica* (Common buckthorn), a limestone pavement specialist species, was identified as an indicator species for this group and was found on all of these pavements apart from Bastow Wood. Species richness was high on the Group 4 limestone pavements (mean 66 species, +/-6.7 species), larger than all the classes except for Group 6, and with mid-range rare species identified. None of the limestone pavements in this group were grazed, and emergent height was greatest of all the groups with mean height in Group 4 significantly larger than Groups 7, 6 and 1 (ANOVA, $F(5,37)=11.582$, $p<0.001$; Games-Howell, $p<0.05$).

Figure 5-20: LIS positioned on the centre of Hampsfield Wood limestone pavement, Group 4, showing the high percentage of mossy cover on the clints.

Analysis of Group 4 using the MAVIS computer programme (Centre for Ecology and Hydrology, 2000) resulted in the same homologous score as the Group 8 pavements, vegetation class 35, corresponding to 'diverse base rich woodland/hedges' under the CVS. The CVS only considers selected mosses in its classification, accordingly a number of species recorded on Group 4 limestone pavements were excluded from the MAVIS analysis. (Bunce *et al.*, 1999).

This limestone pavement class had the highest percentage of vegetation across the LIS, significantly higher than Groups 1, 6 and 3 (mean 68.6%, +/- 34.8%). Group 4 had the most vegetation on the clints, predominantly mosses, with up to 99.4% of the LIS covered in vegetation on Hampsfield Wood as illustrated in Figure 5-20.

5.8 Summary of Holistic Classification

The assimilation of the above analyses resulted in a new method to classify 43 of the limestone pavements studied and the pathway to the six limestone pavement holistic functional groups is summarised in a flowchart in Figure 5-21. From the research data that were collected it was not possible to classify three of the limestone pavements in the study - Colt Park Wood (IBCOLT), Moelfre (NWMOE) and Boncs (NWBON), limestone pavements that are exceptional.

It is anticipated that the flowchart will allow holistic classification of limestone pavement to be carried out in the field. Conservationists armed with knowledge of key aspects of the pavement including altitude, coastal proximity, grike depth and plant composition are directed through the flowchart towards one of six classes. The holistic classes advance the understanding of the nature of this habitat but, like any functional grouping, may have some limitations. The trial and use of both the classification and the flowchart over time should be beneficial for their development and refinement.

Limestone pavements are also classified by the European Nature Information System (EUNIS) under the level three habitat code - ‘Almost bare rock pavements, including limestone pavements’ (Hill *et al.*, 2004). The EUNIS habitat types classification is a comprehensive pan-European system recognised across Europe using set criteria for habitat identification. It covers all types of habitats from natural to artificial, from terrestrial to freshwater and marine. A tabular classification relating to the EUNIS codes is presented in Table 5-20. This considers limestone pavement under the biotope model (Connor *et al.*, 1997) which combines habitat and species in a holistic approach, relevant given the nature of limestone pavements. It is suggested here that there is an opportunity to amalgamate the holistic classification drawn up in this research with the EUNIS habitats classification.

Further to this, it is hoped that this method of grouping limestone pavement habitat can be generalised to other limestone pavements across North West England and North Wales. With further research, this classification has the potential to be used worldwide.

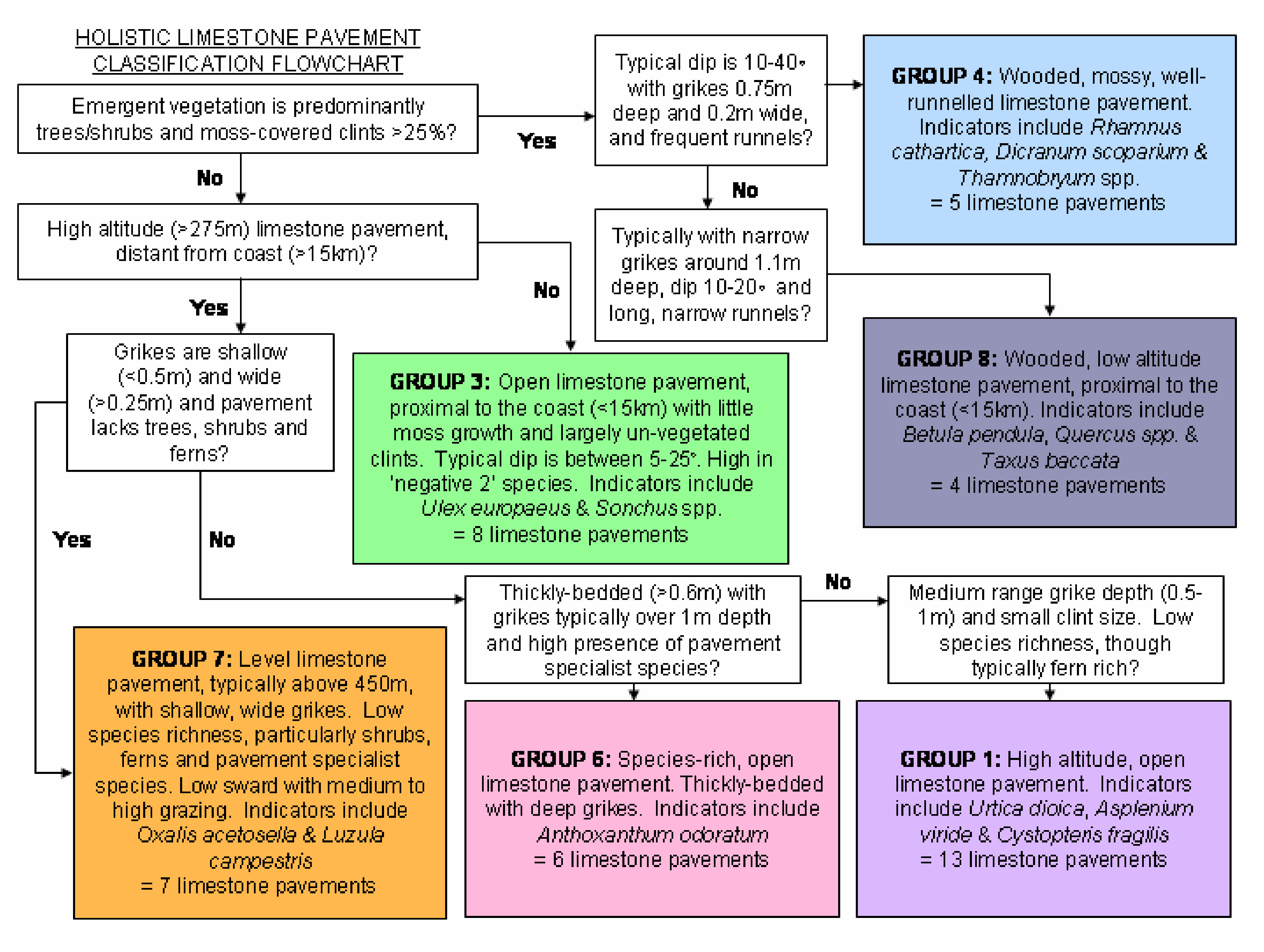

Figure 5-21: Flowchart of holistic classification and summary of limestone pavement groups

Table 5-20: Potential correlation with EUNIS habitat classification (Hill *et al.*, 2004).

EUNIS = H3.5	***'Almost bare rock pavements, including limestone pavements'***	
LP1	**Limestone pavement with emergent vegetation which is predominantly trees and shrubs and with moss covered clints >25% = Wooded Limestone Pavement**	**WLP**
LP1.1	Wooded, mossy, species-rich limestone pavement. Typically dip is 10-40°, grikes 0.75m deep and 0.2m wide, and runnels are frequent. Indicators include *Rhamnus cathartica*, *Dicranum scoparium* and *Thamnobryum spp*.	WLP.G4
LP1.2	Wooded, low altitude limestone pavement, proximal to the coast (<15km). Typically with narrow grikes around 1.1m deep, dip 10-20° and long, narrow runnels. Indicators include *Betula pendula*, *Quercus spp*. and *Taxus baccata.*	WLP.G8
LP2	**Limestone pavement with predominantly un-vegetated clints and tree/shrub/moss cover <25% = Open Limestone Pavement**	**OLP**
LP2.1	Open limestone pavement, proximal to the coast (<15km) with little moss growth and largely un-vegetated clints. Typical dip is between 5-25°. High in 'negative 2' species, lower levels of precipitation and ground frost. Indicators include *Ulex europaeus* and *Sonchus spp*.	OLP.Co.G3
LP2.2	**High altitude (>275m) limestone pavement, distant from coastal margin (>15km).**	**OLP.Up**
LP2.21	Level limestone pavement, typically above 450m, with shallow, wide grikes, generally <0.5m deep and >0.25m wide. Low species richness, particularly trees/shrubs/ferns and pavement specialist species. Low sward (<40mm) with medium to high grazing. Indicators include *Oxalis acetosella* and *Luzula campestris*.	OLP.Up.G7
LP2.22	Species-rich, open limestone pavement. High presence of limestone pavement specialist species. Thickly-bedded (>0.6m) with grikes typically over 1m deep. Indicators include *Anthoxanthum odoratum*.	OLP.Up.G6
LP2.23	High altitude, open limestone pavement with medium range grike depth (0.5-1m) and small clint size. Low species richness, though typically rich in fern species. Indicators include *Urtica dioica*, *Asplenium viride* and *Cystopteris fragilis*.	OLP.Up.G1

6 LINKING LIMESTONE PAVEMENT MANAGEMENT WITH THE HOLISTIC CLASSIFICATION

6.1 Introduction

This chapter examines research behind the most current management practises on limestone pavement habitats and relates this to the findings of this study. It outlines positive conservation management techniques which maximise the geodiversity and the biodiversity value of limestone pavements, and gives details of best practise management guidelines where these are available. Specific aspects are explored which include animal grazing and how to deal with less favoured species or promote positive species. These management objectives are then related, in turn, to each of the six holistic classes described in Chapter 5. The aim of this chapter is to assist conservation agencies to make the best holistic decisions in order to effectively manage all types of limestone pavements.

Over the past twenty years several important papers have been written which consider the management of limestone pavements across Britain and the Republic of Ireland (Burek *et al.*, 1998; Burek & York, 2009; Conway & Onslow, 1999; Crawford & Burek, In review; Dunford, 2001; Goldie, 1994; LPAG, 2003, 2005; Murphy & Fernandez, 2009; Smith *et al.*, 2007; Thom *et al.*, 2003; Van Rensburg *et al.*, 2009; Webb & Glading, 1998). They have explored a number of issues concerning limestone pavement which include:

- Are limestone pavements across the UK and Republic of Ireland protected sufficiently to prevent them suffering further mechanical damage by removal of stone, destruction or infilling?
- Are the same conservation management techniques appropriate for different types of limestone pavement?
- Should some limestone pavements be managed as landscape features or archaeological sites?

- Limestone pavements have a fascinating evolutional history. Ought sites be managed to demonstrate this?
- Should limestone pavements be managed solely for their palaeontology interest?
- Do limestone pavements benefit from being grazed, and if they do, what form of grazing? What about timing and what are the optimal grazing levels?
- What happens on totally un-grazed limestone pavement? Does it revert to a woodland habitat or become overgrown with non-priority species?
- If grazers are to be excluded from limestone pavement then what is the best way to do this, considering limestone pavement is often a valuable landscape feature and is often in a mosaic with other open habitats?
- Should less-favoured herb, shrub or tree species such as Bracken, Cotoneaster and Gorse be removed from limestone pavements and if they should then how?
- Is it appropriate to perform coppicing on some limestone pavements?
- Are there particular management considerations for individual target species or taxonomic groups e.g. particular BAP species?
- How can the success of the management strategies be assessed and what is the optimal condition for different types of limestone pavement?
- What will the effects of climate change be on limestone pavements?

A number of these key questions remain wholly or partly unanswered across the full range of limestone pavements. The aim of this research was to identify whether the holistic classification of limestone pavement would help to clarify the most effective management strategies for different classes of limestone pavement. It was considered that classification would enable the limited resources of conservation agencies to be targeted more effectively, thereby achieving the best outcome to conserve both the geodiversity and the biodiversity of limestone pavements.

6.2 *Management Objectives on Limestone Pavement*

6.2.1 Protecting Limestone Pavement from Physical Damage

Historically, limestone pavement has been subjected to considerable threat from destruction by removal of stone (e.g. for walling, lime production, decorative uses and building - see Figure 6-1) and by the infilling of grikes by farmers wishing to prevent damage to grazing stock (Goldie, 1994; Gray, 2004; LPAG, 2004). Spiteri (1991) noted some additional physical threats to limestone pavement which included the dumping of manure on the pavement (possibly as a result of restriction in application elsewhere on the farm), use of the pavement as a bonfire site and pesticide/fertiliser drift onto pavement areas, which can eliminate desirable plant species whilst allowing invasion by weedy species such as Thistle and Nettle.

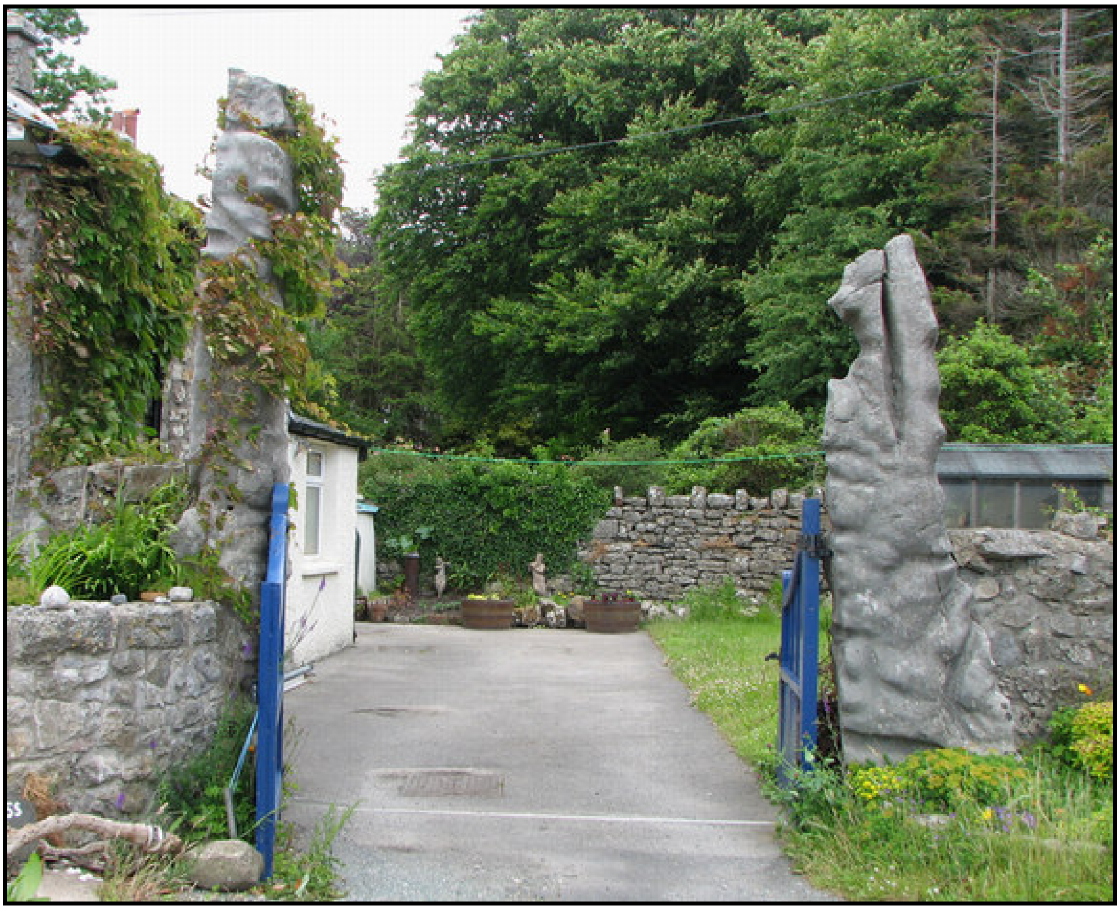

Figure 6-1: Large clints removed from a limestone pavement prior to the current legal protection, being used as decorative gateposts at a house in Morecambe Bay.

Since the extensive damage to limestone pavements in Britain and Ireland in the latter part of the twentieth century (Ward & Evans, 1975), the legal protection of limestone pavement, in some geographical areas, appears to be working (Crawford & Burek, In review). In England the limestone pavements that are classed as important for their biodiversity have unprecedented protection in law by Limestone Pavement Orders (LPOs) and minimal physical damage has occurred in these areas since implementation of the LPOs (Crawford & Burek, In review).

This protection does not extend to other parts of the UK, but some limestone pavements in these areas have been designated as Regionally Important Geodiversity Sites (RIGS). UKRIGS is now known as GeoConservationUK and was set up in the 1990s to conserve earth science. RIGS are not protected by law but are increasingly given protection by local authorities through planning guidance. There are groups throughout England, Scotland and Wales (Burek, 2000; Burek & Prosser, 2008; Gray, 2004).

Figure 6-2: Limestone pavement on the Burren that has been bull-dozed into piles ready for removal. Photograph courtesy of S. Ward, 2007.

Protection from physical damage to limestone pavement has not yet been completely resolved across Britain and Ireland, as is illustrated in the photograph in Figure 6-2, taken by Stephen Ward, chairman of the UK-Ireland Limestone Pavement Group in 2007. Limestone pavement is being broken up and removed, often for use as rockery stone or in the process of ground clearance for agriculture/house building (Pendry & Allen, 1999). Internet search by the author in November 2010 demonstrated companies still openly and actively selling 'Irish water-worn limestone rockery stone', almost certainly sourced from destroyed limestone pavement.

Murphy and Fernandez (2009), on behalf of the National Parks and Wildlife Service in Ireland, reported that limestone pavement in the Republic of Ireland totals 31,100 ha, most of which lies in the Burren. Over 10% of this lies outside any designated area and therefore has no protection in law (UK-Ireland Limestone Pavement Biodiversity Group, 2009). The UK-Ireland Limestone Pavement Biodiversity Group, which includes representatives from each of the country agencies, continues to work towards extending the protection afforded to English limestone pavements to those throughout Britain and Ireland. The application, in 2010, for the Burren to be awarded UNESCO World Heritage Site status can only help to support this cause (UNESCO, 2010).

Figure 6-3: Large patch of clints removed from limestone pavement at Great Asby Scar.

Within this study, the limestone pavements across North West England have received protection from further damage since LPOs were granted in the 1990s. Observations during fieldwork suggest that the amount of stone removal from individual limestone pavements relates to the accessibility of the site and the ease of removal of the stone from the limestone pavement. Thickly-bedded limestone pavements, such as those in Group 6, have received less damage historically, probably due to difficulties of extraction. Conversely, limestone pavements on the remote Cumbrian Fells such as Great Asby Scar, part of the Group 1 pavements, suffered greatly at the hands of opportunist thieves (see Figure 6-3).

Some of the limestone pavements in Group 3 remain the most at risk of those across the study group, as pavements in Wales are not protected by LPOs. Bryn Alyn, Great Orme and Taranau are all designated RIGS and the Association of Welsh RIGS groups and GeoConservationUK have worked extensively with landowners, farmers and local communities to educate those involved in protecting these valuable geodiversity sites (Burek, 2000; Burek, 2008; Deacon & Burek, 1997). Major strides were taken in the area of geoconservation in Wales when GeoMôn (Anglesey's Geopark) was accepted as a member of the European Geoparks Network in 2009.

6.2.2 <u>Valuing the Geodiversity of Limestone Pavement</u>

In order to identify the finest examples of karst in the UK a review of potential sites was undertaken by the Joint Nature Conservation Committee (JNCC) under the Geological Conservation Review (GCR) and sites that were identified as suitable were designated as Sites of Special Scientific Interest (SSSI) (Waltham *et al.*, 1997). These include a number of the limestone pavements included in this research, namely the Ingleborough Karst, Malham Cove, Hutton Roof, Farleton Fell and Gait Barrows.

Outside of the GCR, the value of the geodiversity of limestone pavements has been recognised through RIGS and by Local Geodiversity Action Plans (LGAPs) (Burek & Potter, 2006; Kidd *et al.*, 2006; Potter & Burek, 2006). These are usually based on a county or similar geographical area, and they provide a long-term framework for geoconservation (Burek, 2006; Stace & Larwood, 2006).

Kidd, Cooper and Brayson (2006) state that "it is a widely held, but erroneous, popular view that geological features are 'permanent' and are not in need of the level of conservation afforded to biodiversity". Indeed, many limestone pavements do receive protection because of their rich biodiversity, but sometimes there are conflicting conservation objectives between geodiversity and biodiversity at protected sites. Burek (2000) cites Bryn Pydew as an example of this. Bryn Pydew is a species-rich wooded limestone pavement in North Wales (Group 8 in the classification). Here the conflict occurs as plants such as Ivy (*Hedera helix*), Clematis (*Clematis vitalba*) and Bramble (*Rubus fruticosus*) threaten to mask the geodiversity at the site. Management objectives should therefore be clearly set and should consider the site as a holistic entity, not solely with biodiversity aims (Burek, 2000).

Assessment tools that measure the geodiversity of limestone pavements are uni-disciplinary and often quite technical (A. Kidd, 21st November 2006, pers. comm.). This is also the case with biodiversity assessment of limestone pavements such as the Common Standards Monitoring (CSM) tool (JNCC, 1997). It is for this reason that Ellis (2007) developed the Pavement Formation Assessment (PFA) discussed in previous chapters and trialled/modified during the course of this research. The PFA is a brief assessment which can be undertaken by any discipline visiting a site. It rates the extent of the limestone pavement that is continuous and its physical condition, i.e. how broken the pavement is. During the course of the PFA trial period in this study it was identified that rating the geomorphology at the limestone pavement would offer a further qualitative assessment of the limestone pavement, and this was added to the PFA (see Appendix H). It is hoped that this monitoring tool will be of benefit to conservation agencies in their holistic assessment and monitoring of limestone pavement habitats.

One key to the protection of limestone pavements is public awareness and education (Lancashire Biodiversity Partnership, 2008; LPAG, 2003, 2005; Van Beynen & Townsend, 2005), and part of this is addressed by encouraging visitors to come onto limestone pavement to experience the habitat first-hand. This research examined the impact of visitor numbers on the limestone pavements studied and found no measurable impact at any site in terms of quality of the flora or integrity of the pavement. It should be noted that there was no measure of the impact of footfall on the lichen communities of limestone pavement during this research.

Figure 6-4: Litter lodged in a grike.

Limestone pavements with high visitor levels did have significantly more litter on and around the site, detracting from their aesthetic appeal. At Malham Cove, 87 pieces of litter were seen, primarily food and drink packaging lodged in the deep, narrow grikes and therefore difficult to remove (Figure 6-4).

Figure 6-5: Visitors to the limestone pavement at Malham Cove.

Malham Cove limestone pavement is probably the most well known limestone pavement in Britain and visitor numbers were observed to be very high (Figure 6-5). This limestone pavement would undoubtedly benefit from management of the litter problem.

Another aspect to valuing limestone pavement is in the consideration of the associated 'built heritage' of the site e.g. the presence of lime kilns or dry stone walls which may contain clints or erratic stones from the pavement itself. Examples of this were seen on the Great Orme, where fossiliferous limestones had been used in the construction of boundary walls (Figure 6-6). These features are of added value to a site's geodiversity and history, enhancing public interest and education.

Figure 6-6: Fossils in the drystone walls at the Great Orme

One of the least valued elements of limestone pavement geodiversity is their soils, key to the habitat and the biodiversity of the site (Conway, 2009). Conway notes that there is now some recognition from the conservation agencies that soil is "one of nature's greatest natural assets", and adds that Welsh RIGS groups have incorporated soils into their geoconservation work (Burek *et al.*, 1998; Burek & Legg, 1999a; Conway, 2009). However, recording the soil type is not a practise incorporated into existing monitoring protocols on the majority of limestone pavements and this is a notable omission.

6.2.3 <u>Managing the Biodiversity of Open Limestone Pavement</u>

One of the measurement tools used during this research was to identify the five tallest emergent species on the limestone pavement (see Section 4.5). Where negative species were the modal tallest species (Nettle, Thistle, Bracken or Gorse) the sward height was found to be significantly shorter compared to limestone pavement with trees as the modal tallest species. Additionally the soil depth in the grikes increased. These are both indications of sub-optimal limestone pavement management. It is therefore proposed that recording modal emergent species is added to the monitoring of limestone pavement habitats to assist conservation managers in identifying sites that require remedial management actions.

6.2.3.1 Sheep Grazing

Considerable evidence links medium to high levels of grazing by sheep and rabbits to a decline in biodiversity on limestone pavement (e.g. Burek & Legg, 1999a; Conway & Onslow, 1999) and this association has been significantly reinforced by the research carried out in the course of this study (see Chapters 4 and 5). This research identified a statistically significant relationship between height of sward (as a surrogate for grazing intensity) and species richness, with a highly statistically significant positive correlation between sward height and abundance of rarer species (A and B species) dependent on limestone pavement for their continued existence.

Conway and Onslow (1999) stated that on the Welsh pavements that they assessed "pavements with sheep grazing were nearly always over-grazed. The only pavements that were not over-grazed were either fairly inaccessible or had deep grikes such as Bryn Alyn".

Silvertown (1982) examined the relationship between certain plant species and limestone pavement geomorphology. He demonstrated Ward and Evans' (1976) hypothesis concerning the association between grike dimension and grazing. These authors agree that sheep can only graze to a depth equal to grike width in grikes that the sheep cannot enter bodily; and Silvertown defines the depth zone accessible to sheep as "rarely deeper than 30cm". Silvertown suggests that grazing may eliminate species from an area in two ways, either by outright removal of all plants present or by reducing the plant density to such a low level that the population is not sustainable.

Miller, Geddes and Mardon (1999) state (of limestone grasslands) that "sheep undoubtedly cause damage – they defoliate, uproot, trample and bury seedlings". They conclude that it is beneficial to reduce grazing pressure when target species are growing, flowering and setting seeds, which is generally June/July. Conversely it might be desirable to drive sheep onto sites in late August and early September. This increases grazing and trampling at that time, increasing the area of bare soil for seedling colonisation and reducing competitive vigour of perennial vegetation (English Nature, 2004). This strategy has been adopted by Natural England under their agri-environment schemes for limestone grasslands and in certain circumstances may be a relevant management option on limestone pavement habitats, particularly where they exist in a mosaic with calcareous grassland.

Dunford (2001) notes that sheep were historically the dominant grazer of Burren uplands and he examined the value of supporting sheep grazing as a means of dealing with the problem of scrub encroachment in the Burren. After examining the evidence, Dunford concluded that although sheep may have some efficacy in the control of Hawthorn (*Crataegus monogyna*) their selective grazing reduced certain preferred species, including Orchids. Allied with their tendency to defecate in particular areas, leading to localised enrichment, these findings led Dunford to conclude that there was insufficient evidence to support sheep grazing as a conservation measure on the Burren.

In summary, sheep grazing is therefore not recommended on limestone pavements where biodiversity is the prime management objective, except in certain circumstances where the overdevelopment of scrub is threatening biodiversity objectives (Lancashire Biodiversity Partnership, 2008). In this situation, the numbers of sheep and the timing of the grazing should be considered carefully.

6.2.3.2 Cattle Grazing

Cattle grazing, using hardy traditional breeds of cattle, is considered best practise to maximise limestone pavement biodiversity on open limestone pavements and limestone grassland habitats (GAP, 2009; Graham *et al.*, 2007; Milligan, 2003). Traditional breeds include Aberdeen Angus, Beef Shorthorn, Belted Galloway, Blue Grey (illustrated Figure 6-7), Devon, Dexter, Galloway, Hereford, Highland, Luing, Red Poll and Welsh Black (Van Rensburg *et al.*, 2009). They are primarily raised for meat, as beef cattle have lower nutritional requirements than dairy herds, so can be sustained on the relatively low nutrition available in these limestone habitats (English Nature, 2004).

Figure 6-7: Blue Grey, brought in to graze limestone grasslands around Tennant Gill limestone pavement under the Limestone Country Project in the YDNP.

Cattle grazing was initially encouraged under the Wildlife Enhancement Schemes (Smith *et al.*, 2004) (now HLS schemes) and was an integral part of the Limestone Country Project, an EU LIFE funded project, in the Yorkshire Dales (Graham *et al.*, 2007). Under this project, traditional breed cattle grazing was found to increase both biodiversity and abundance of favoured limestone species present, when compared to sheep grazing (Bevan & Hibbins, 2008). Cattle graze in a different way to sheep, rolling the sward around their tongues and pulling at the vegetation, leaving bare ground suitable for recolonisation (Dunford, 2001). Mercer and Evans (1997) describe this as a "light poaching and non-selective grazing approach" which maintains good conditions for plants in limestone habitats.

Investigation into the movement patterns of cattle using GPS collars also confirmed anecdotal evidence that, unlike sheep, cattle generally avoid the unstable clints and grikes of limestone pavement (Bevan & Hibbins, 2008). This therefore leaves plants in grikes untouched, compared to sheep which will graze all accessible pavement areas (Dunford, 2001) as can be seen in Figure 6-8.

Figure 6-8: Sheep grazing at Top Cow, one of the thickly-bedded limestone pavements in Group 6.

Dunford (2001) summarises the other aspects requiring consideration in conservation cattle grazing regimes, which includes the herd's knowledge and familiarity with a site, as mature cattle are more effective in leading the herd around an area. Parr (4th May 2007, pers. comm.) adds that mature cattle (over 18 months old) are better at grazing rank grasses as they have a full set of teeth.

6.2.3.3 Rabbit Grazing

Brandes (2000) noted a difference between floristic quality on adjacent pavements at Kingsdale, North Yorkshire. This was apportioned to the difference in rabbit grazing caused by differences in geomorphology. Where the grikes were wider and shallower rabbits were able to colonise, burrowing and grazing on the pavement. This was observed to be associated with higher level of Nettle and Thistle with no ‘A species’ (rarities).

Thom, Swain, Brandes, Burrows, Gill, and Tupholme (2003) estimate that for every ten rabbits seen on the surface there are one hundred below ground, whilst Dunford (2001) estimates that ten rabbits are the equivalent of one sheep. Thom (14^{th} November 2006, pers. comm.) notes that rabbits are a particular problem in the Yorkshire Dales as farmers tend to kill the foxes, the rabbit’s main predator. Rabbits prefer short grass, not the tall rank grasses. Rabbit numbers are also increasing because of climate change as they are now capable of reproducing all year round. Culls are sometimes arranged for conservation reasons but this is not popular with some farmers who themselves have an income from rabbits, as it reduces the value of rabbit meat on the black market.

Thom (2009) concluded that “rabbits are, and will continue to be, a major problem for the Yorkshire Dales National Park Authority”. The Limestone Country Project successfully reduced numbers within the areas targeted but Thom suggested that numbers would quickly rise again if not kept in check, something that would require high levels of coordination over a wide geographical area, not generally available except under the auspices of a special project (Thom, 2009).

Webb and Glading (1998) state that “rabbits appear to be ubiquitous on both upland and lowland limestone pavements”. They add that rabbit grazing is particularly damaging to the ecology of the pavements because of the scuffing and burrowing behaviour which can “accelerate vegetation recession”. These authors also advocate rabbit control for optimal management (Webb & Glading, 1998).

In summary, rabbit grazing poses a problem to limestone pavement biodiversity, akin to the effects of sheep grazing. Sheep and rabbit grazing styles are similar in their selectivity and close cropping of the vegetation (Dunford, 2001). It is therefore important to monitor rabbit numbers on limestone pavements and use control methods where biodiversity is impacted.

6.2.3.4 Goat Grazing

Goats have been traditionally employed across Europe, and notably on the Burren, to control scrub, and feral herds are found on the Burren and Great Orme, Llandudno, North Wales. Goats are generalist grazers and feed on the most palatable vegetation available, which can include stripping bark from trees in woodland areas (Bullock & O'Donovan, 1995). They have been found to have value as conservation grazers when large densities of goats were introduced to an area of scrub when other more palatable species were dormant (Vallentine, 1990).

Figure 6-9: Feral goat herd on the limestone pavements of the Great Orme SSSI.

Dunford (2001) discusses the relative merits of goat grazing in the Burren and summarises that "the use of goats to reverse scrub encroachment on certain selected sites should be investigated…and their impacts closely monitored".
Within this study, goat grazing was only encountered on the Great Orme, where grazing was noted to be at medium levels with minimum sward height at 100mm. The feral goats on Great Orme are embedded in the history of the area and are a tourist attraction in their own right (see Figure 6-9). A small

area of the Great Orme has been fenced off for over 15 years, yet plant and mollusc communities examined within this area during this study were found to be very similar to the rest of the limestone pavement. Conway and Onslow (1999) had the same findings and postulated that this may be due to the exposure at this site. Rhodes (2002) examined the salt spray effect on Great Orme in his research and noted that salinity was significantly higher than on a comparative inland limestone pavement (Bryn Alyn). High levels of salinity cause stress to plants and are likely to be a limiting factor in their growth patterns (Krebs, 1985).

This research offers insufficient new evidence regarding goat grazing to add to the ongoing debate about their value in conservation management. However, from the literature review, there are clear similarities between goat and sheep grazing, so the impact of goat herds on the biodiversity of limestone pavement should be closely monitored. Best practise guidelines on the Burren conclude that "different breeds and types of goat have different grazing and browsing habits: to be effective as conservation grazers, goats need to be managed and this requires a lot of work which is not always realistic" (BurrenLIFE, 2010).

6.2.3.5 Deer Grazing

Deer grazing is an increasingly significant factor on lowland limestone pavements with the increase in deer populations in northern Britain as they browse coppice regrowth and prevent the establishment of saplings (Webb & Glading, 1998).

A study over thirty years on Carboniferous limestone woodlands in Killarney National Park, South West Ireland, concluded that deer grazing was having a major impact on natural regeneration (Perrin *et al.*, 2006). The study summarised that heavy levels of deer grazing favoured the regeneration of unpalatable species, but did not advocate exclusion of deer as the ideal management option, advising that "this can lead to the development of dense ground vegetation, moss and litter layers which can prevent subsequent seedling establishment through the elimination of microniches" (Perrin *et al.*, 2006). Instead the study suggested a reduction in populations to levels where there is light browsing of saplings only, but sufficient trampling and grazing of the field layer to maintain seedling establishment. From their research, Perrin, Kelly and Mitchell (2006) added that evidence suggests that grazing level was not the only significant factor in regeneration of woodland. The density of the canopy and natural regeneration dynamics should also be taken into consideration.

Deer fencing and culling were found to be effective management tools under the Morecambe Bay LIFE Project and positive indicators such as growth of Yew were seen where deer control measures were undertaken. The authors suggest that the benefits of deer culling were not site specific as they were seen across a wider geographical area. They advocate a coordinated approach across the district and value the local deer management groups who monitor and act as required in the Arnside-Silverdale and South Lakes areas (Milligan, 2003). Detailed advice on managing problems caused by deer is contained in a technical information document published by Natural England (Natural England, 2008).

6.2.4 Managing Biodiversity on Wooded Limestone Pavement

Key issues facing wooded limestone pavements include scrub encroachment and the commercial planting of limestone pavements and their surrounds with non-native species (Milligan, 2003). Lack of grazing or unsympathetic management on lowland limestone pavements has resulted in overgrowth of species such as Hazel, Bramble, Blackthorn and Hawthorn leading to reduced biodiversity, notably on the Burren (Dunford, 2001), on Bryn Pydew in North Wales (Burek, 2000; Burek & Conway, 2000a) and on the limestone pavements around Morecambe Bay (Lancashire Biodiversity Partnership, 2008; Milligan, 2003). Tree species such as Pine (*Pinus*), Larch (*Larix decidua*), Western Red Cedar (*Thuja plicata*) and Beech (*Fagus sylvatica*) have a dense waxy leaf fall and intense shade which stifles the flora in limestone pavement grikes leading to biodiversity loss (Webb & Glading, 1998). Two EU funded projects have examined these two issues and their management - BurrenLIFE and the Morecambe Bay LIFE Project, and outcomes from these projects are summarised here.

Issues on the Burren are largely due to reduced grazing management resulting from changes to traditional farming practises over the past few decades (Williams *et al.*, 2009). This has led to scrub encroachment and reduced biodiversity on limestone pavements and limestone grasslands on the Burren (Van Rensburg *et al.*, 2009). The BurrenLIFE project experimented with management regimes on 20 farms encompassing 3,000 ha. The results of this research have produced a number of 'Best Practise Guides' for farmers, outlining important methods to improve the conservation status of the Burren habitats (Hill *et al.*, 1999).

Grazing cattle are part of the traditional heritage of the Burren and strategies for conservation management with cattle involve changing from silage feed, which was leading to eutrophication of habitats, to specially formulated concentrate feed. Alongside techniques of animal husbandry grazing can be targeted appropriately (BurrenLIFE, 2010). The timing of stock movements onto and off the Burren 'winterages' is a significant factor for both the control of scrub and to ensure seed setting is not disturbed. The BurrenLIFE project has outlined these aspects comprehensively in their 'Best Practise Guide no.3 - Sustainable Grazing of Burren Winterages' (BurrenLIFE, 2010).

The Morecambe Bay LIFE Project aimed to remove non-native species from limestone pavement areas and deal with scrub encroachment by instigating traditional, rotational coppicing and thinning management techniques. It also introduced traditional breed cattle grazing as a restoration tool, in a scheme similar to the Limestone Country Project discussed in Section 6.2.3.2. Work was undertaken on a number of limestone pavement sites in this study area including Dalton Crags, Hampsfield Wood (Group 4), Farrar's Allotment, Gait Barrows, Underlaid Wood (Group 8) and Hutton Roof Crags (Group 3) (Milligan, 2003).

Webb and Glading (1998) present the ideal management of lowland woodland limestone pavement in their paper and give Gait Barrows National Nature Reserve as an example of positive conservation management. They state that regular coppicing and thinning should be conducted to maintain open glades with woodland edges, which can be an important habitat for biodiversity. It is the rich mosaic of open pavement, grassland, scrub and woodland that is important for biodiversity on wooded limestone pavements.

The key to the management of wooded limestone pavement is maintaining optimal levels of scrub and structural variation to avoid the consequent loss in biodiversity that had been seen on limestone pavements in the Burren and Morecambe Bay areas prior to remedial management (Milligan, 2003; Williams *et al.*, 2009). Outcomes from the Limestone Country Project (Smith *et al.*, 2008) indicated that no grazing (or traditional breed cattle who do not go onto limestone pavement) resulted in the greatest species richness on limestone pavements. Results from this research and literature review indicate the importance of monitoring vegetation development on un-grazed limestone pavements by considering vegetation composition, structure and distribution and then implementing conservation management as necessary. Natural England's limestone pavement 'Condition Assessment' already considers these aspects on limestone pavement (JNCC, 1997, 2009).

6.2.5 Dealing with Less Favoured Plant Species

Methods for removing harmful weeds such as Ragwort, Thistle and Nettle are well documented (e.g. DEFRA, 2007) and can be adopted for use in limestone pavement habitats. Bracken, Cotoneaster and non-native tree species pose a more specific challenge on limestone pavement habitats and the management issues are outlined below.

6.2.5.1 Bracken

Bracken (*Pteridium aquilinum*) is a plant of acidic, well-drained, preferably deep soils so it generally avoids limestone. However, it will grow on glacial drift overlying limestone, and there are pockets of Bracken overgrowth on limestone pavement areas. This is a factor of concern in conservation management due to its invasive nature (Canaway, 2006; Scottish Government, 2008). The control of Bracken was considered important on some of the lowland wooded pavements in Morecambe Bay and this was dealt with by physical methods, namely Bracken bashing (Milligan, 2003). Bracken on areas of limestone grassland adjacent to the limestone pavement can be effectively dealt with within restoration cattle grazing techniques by careful positioning of water sources and mineral licks. Cattle can thus be encouraged to congregate in Bracken areas, a traditional method which tramples and crushes the fronds during the growing season, thus depriving the rhizomes of their food supply (Canaway, 2006; Milligan, 2003; Scottish Government, 2008).

Comprehensive guidelines on removal or treatment of Bracken have been provided by the Scottish Government in the form of a 'Best Practise Guide' (Scottish Government, 2008).

6.2.5.2 Cotoneaster

Crofts and Jefferson (1999) reported that a particular problem on lowland carboniferous limestones is the establishment and spread of a range of shrubs belonging to the genus *Cotoneaster*. The authors add that over a hundred species are widely cultivated in Britain, and most have the potential to become established in the wild, particularly *C. integrifolius* (often recorded as *C. microphyllus*) and *C. horizontalis*. Berries from the shrub are highly attractive to blackbirds and thrushes so they are readily dispersed and once established, may result in extensive smothering of native communities. The root systems are highly pervasive, often penetrating deeply into crevices in the limestone (Bond, 2003; Crofts & Jefferson, 1999).

In Wales it poses a significant risk to the native wild Cotoneaster (*Cotoneaster cambricus*), a UKBAP species. Field trials into the eradication of this invasive species were commissioned by English Nature (now Natural England) and they found it a difficult plant to control, but had the best results from herbicide application (Bond, 2003). Webb (12th June 2009, pers. comm.) recommends that a neat solution of herbicide painted on the stumps of the plants after cutting back is effective.

6.2.5.3 Non-Native Tree Species

Dealing with non-native tree species in conservation environments poses particular challenges and the Morecambe Bay LIFE Project has dealt with this in a number of ways, dependent on individual circumstances. Techniques for larger trees included ring barking, by running a chainsaw around the tree trunk to interrupt the sap. At Gait Barrows this avoided the need for chemical intervention in an area that was applying for organic status. Ring barking leaves the deadwood *in-situ*, an ecologically sound practise as it is an important habitat for biodiversity (Yorkshire Dales National Park Authority, 2000). Residue from felling and coppicing operations (brash) was removed by various means including mechanical, burning, use in dead-hedging and by chipping, the latter for use in the biofuel industry (Milligan, 2003). Brush mats are sometimes used to facilitate removal of trees from a site. Conway (15th November 2007, pers. comm.) considers it imperative to remove the mats after the operation to prevent this brash rotting down into the grikes, as it is likely to affect the soils in the grikes, negatively impacting vegetation.

6.2.6 Managing Limestone Pavements for Target Species

Limestone pavement is a rich environment for fauna due to the micro-habitats available, particularly on wooded sites (Webb & Glading, 1998; York, 2009). In a report submitted to the UK's Upland Biodiversity Integration Group (BIG), the following species were identified as particularly associated with limestone pavement habitats (Webb, 2008). They were:

- *Polystichum lonchitis* - Holly-fern
- *Boloria selene* - Small Pearl-bordered Fritillary
- *Argynnis adippe* - High Brown Fritillary
- *Boloria euphrosyne* - Pearl-bordered Fritillary
- *Collema fragile* - a lichen
- *Synalissa symphorea* - a lichen

Webb (2008) summarised that "it was difficult to reach any summary about their combined habitat requirements" and these are aspects of limestone pavement ecology that remain relatively un-researched. Those species that have been identified as being associated with limestone pavement habitats (e.g. Lancashire Biodiversity Partnership, 2008; Yorkshire Dales National Park Authority, 2000) vary across different geographical locations and this section describes some of the initiatives and actions conducted in limestone pavement habitats in the study area.

As a case study using the holistic classification, this research project examined mollusc populations on eleven limestone pavements in Yorkshire (see Chapter 7). Analysis of snail community data with the limestone pavement geodiversity and plant findings identified that molluscs respond to the same key factors on limestone pavements as plants. Factors include altitude, exposure and depth of grikes. Mollusc communities generally benefit from the same management techniques that aim to maximise plant diversity (Willis & Norris, 2009).

In another study, a large population of the nationally rare snail species *Vertigo angustior*, was discovered at Gait Barrows limestone pavement (Killeen, 1997) and management objectives were established under the Morecambe Bay LIFE Project in order to conserve this species. *V. angustior* is associated with the mossy habitat underneath the branches of Yew trees so deer control was undertaken to reduce grazing and allow the canopy to develop (Milligan, 2003).

Other management for target species undertaken under the Morecambe Bay LIFE Project included non-native tree removal, scrub clearance, coppicing and thinning to benefit butterfly populations. Milligan (2003) reported that "the coppicing programme has been one of the most rewarding areas of work within the project. There has been an excellent response in the ground flora, especially those species, such as violets and primroses, used by butterflies". The Project described significant increases in populations of High Brown Fritillary (*A. adippe*) and the Pearl-bordered Fritillary (*B. euphrosyne*) following the remedial work (Milligan, 2003).

Replanting limestone pavements with seedlings of 'preferred' higher plant species is another management technique occasionally employed. Yew, Juniper, Buckthorn, Lancastrian Whitebeam and Spindle were all propagated from native local stock in Morecambe Bay to aid regeneration of limestone pavements there (Milligan, 2003).

The YDNPA (2002) report that Juniper propagation and replanting has also been conducted within the Yorkshire Dales under the UK BAP Species Action Plan, though not on limestone pavement areas. Excessive grazing of Juniper by sheep, rabbits and voles has prevented natural regeneration and prolonged heavy grazing has fragmented stands into scattered individual plants. In some instances where there has been too little grazing the Juniper has been shaded out by overgrowing trees, as it does not tolerate dense shade (Thomas *et al.*, 2007). Clearance of Juniper stands in the Yorkshire Dales has also caused the loss of some colonies, as Juniper now has little or no economic value (YDNPA, 2002).

Orange (2009) outlines the advantages of maintaining open areas on limestone pavement for lichen communities, particularly avoiding dense scrub development such as that caused by the invasive Cotoneaster. Orange provides details of typical limestone pavement lichen/bryophyte communities and includes some uncommon saxicolous lichen and bryophyte species found on limestone pavements. Additionally, Cook (2002) has recorded lower plant species on Bryn Alyn, North Wales.

6.3 Relating Management Objectives to the Classification

6.3.1 <u>Group 7 - A higher altitude limestone pavement group with shallow, wide grikes, typically heavily grazed</u>

The overall features of this group were their high altitude, high exposure and thin bedding planes. Thus Group 7 limestone pavement characteristics were shallow and wide grikes, small clints with minimal solutional features. They were species-poor and lacked the characteristic limestone pavement flora. Aggregate species composition was most similar to ‘moist, neutral to acidic grassland’ (Bunce *et al.*, 1999) but MAVIS analysis showed a diverse range of vegetation types and assigned seven different CVS classes to these pavements ranging from Class 28 (fertile tall herb/grassland) to Class 64 (Bracken/acid grassland) (Centre for Ecology and Hydrology, 2000). Observation suggests that pavement vegetation in this group largely reflected the surrounding habitat type.

Ward and Evans (1975) noted that “shallower grikes (of the Yoredale Group) lack the distinctive features of a damp and shaded microclimate and protection from grazing, which characterise the deeper grikes, and their flora does not differ markedly from the vegetation surrounding the pavement. It is the species of the deeper grikes which distinguish pavements as habitats of great floristic interest”.

Thom (2003) suggested that where grikes are shallow and wide, blue moor grass is likely to be dominant and ‘grassland’ management objectives may be most appropriate in the YDNP, as limestone grassland is also a priority habitat. He stated that reducing grazing at these sites would be most likely to produce species-rich limestone grassland, not limestone pavement floral species. Thom added that a significant number of the pavements within the Yorkshire Dales were of this type.

Figure 6-10: Crinoids visible in the clints at Cam High Road limestone pavement.

Management of Group 7 with regards to their biodiversity should therefore be focussed on the habitat surrounding the limestone pavement. Where this is a priority habitat, such as calcareous grassland, biodiversity objectives should be set to maximise this, which current research suggests should include traditional breed cattle grazing - see Section 6.2.3.2. (Smith *et al.*, 2008).

This limestone pavement group was found to have the richest palaeontology of all the groups, containing good examples of Brachiopods, Crinoids and Corals. It may therefore be appropriate to set geoconservation objectives for some of the limestone pavements in this group with a focus on their fossil content, where this is a significant feature. Some of these pavements are extremely remote yet accessible to the public, so an important management issue for this group is to ensure the fossil rich limestone does not fall prey to opportunist theft. It is notable that historically the exposed limestones from the Yoredale Group were quarried and polished as part of the Dent Marble Industry, because of their fossiliferous nature, and examples were used extensively as fireplaces in waiting-rooms on the Midland Railway (White, 2006).

Where geodiversity is the key focus, management objectives may include sheep grazing to deliberately reduce vegetation and maintain the exposure of the bare limestone bedrock. Weed control (Nettle, Thistle) may also be required to retain the open aspect of the limestone pavement and its features - see Section 6.2.2.

6.3.2 Group 6 - A higher altitude, level, species-rich, thickly-bedded open limestone pavement group

The limestone pavements in this group had deep grikes which afforded a degree of protection from sheep grazing, where this was present, as mean grike depth was around 1m. They were species-rich and Group 6 had the greatest number of limestone pavement specialist species present.

These limestone pavements have the highest quality geodiversity and biodiversity encountered in this study and it is therefore imperative that they are managed optimally to preserve these qualities. Management should therefore follow guidelines in Section 6.2.3 including the removal of grazing or grazing with traditional breed cattle only.

Two limestone pavements within this group were noted to have medium to high levels of rabbit grazing and overall rabbit grazing may be contributing to the high presence of negative 1 floral species that were found on the limestone pavements in this group, notably Nettle and Thistle. Rabbit control, for the reasons outlined in Section 6.2.3.3 is important, especially in the context of climate change, which is likely to exacerbate this problem further.

Additionally, levels of scrub should be monitored closely to ensure the open aspects of the limestone pavement are maintained. Scrub management is discussed in Section 6.2.4.

6.3.3 Group 1 - A higher altitude, open limestone pavement group with mid-range grike depth 0.5-1m and low species richness

The Group 1 classification contains the largest number of limestone pavements and the analysis in the preceding chapter suggests that it is a ‘bucket group’ i.e. high altitude limestone pavement with floral communities that fall between the species-rich Group 6 and the species-poor Group 7.

Management of this group should therefore follow habitat restoration objectives in order to optimise the potential for the biodiversity of the limestone pavement. This entails following the same protocol as Group 6 limestone pavements which includes no grazing or grazing with (preferably traditional breed) cattle and control of less favoured limestone pavement species. Changes to the floral communities should then be monitored. If over time this does not improve the biodiversity of the limestone pavement then it may prove judicious to consider changing the management of the limestone pavement to the Group 7 protocol (T. Thom, 27th September 2010, pers. comm.).

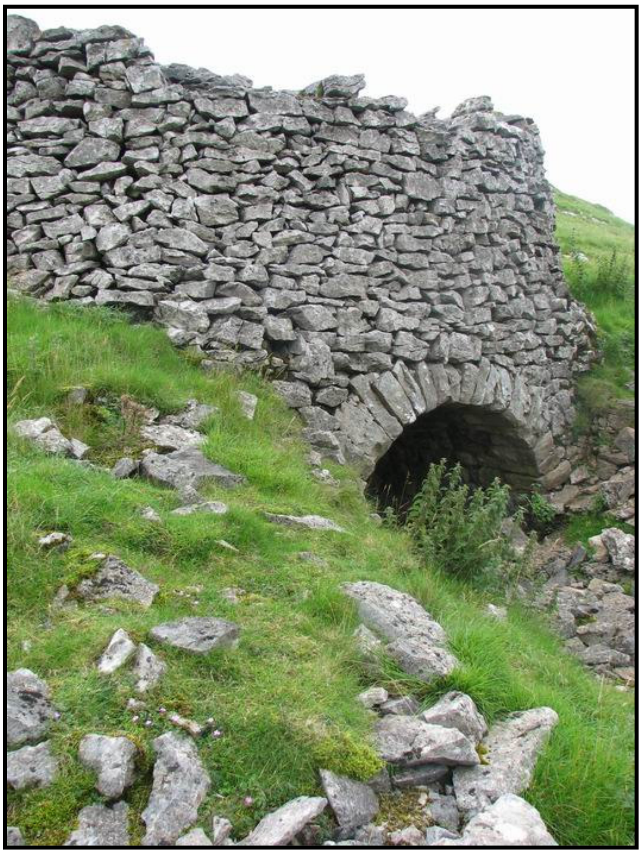

Figure 6-11: Lime kiln adjacent to the limestone pavement at Hill Castles Scar.

Some limestone pavements, such as Hill Castles Scar, have adjacent features of interest such as lime kilns (Figure 6-11). These features are of interest to archaeological historians and tourists, providing evidence of the industrial history of the land (White, 2006). Management of the geodiversity of the limestone pavement should include the protection of these features as they will enhance public interest/education.

6.3.4 Group 3 - An open, coastal limestone pavement group with little moss growth and un-vegetated clints

This group comprises lower altitude limestone pavements that do not fall into the two wooded categories so, like Group 1, constitutes a variable, heterogeneous classification. This group is primarily an open limestone pavement group, though some pavements do have tree and scrub cover, notably Hutton Roof Crags and Taranau in North Wales.

Management objectives to maximise biodiversity value in Group 3 should therefore employ methods outlined in Section 6.2.3. Where scrub and tree cover is a factor then this should be monitored and controlled if necessary.

Where coastal exposure is extreme, as with the limestone pavements of the Great Orme, then it may be unrealistic to expect to be able to positively influence the floral community (Conway & Onslow, 1999).

A key factor in the management of these limestone pavements is to deal with the less favoured limestone pavement species, particularly the ‘negative 2’ species which were at the highest levels in Group 3, notably Gorse (*Ulex europaeus*). Overgrowth of non-priority species not only has a negative affect on biodiversity but also masks the geodiversity of the limestone pavement, having a negative affect on geoconservation. Management should follow that outlined in Section 6.2.5. It was noticed during the fieldwork part of this research that remedial work had already begun on some of the limestone pavements in this group under the Morecambe Bay LIFE project (Milligan, 2003).

6.3.5 Group 8 - A lower altitude, sloping woodland pavement group with Oak and Silver birch predominant

This group can be considered as a ‘classic’ established wooded group, containing Yew and Juniper, both valued limestone pavement species. The climatic conditions are the most moderate of all the groups, all pavements benefiting from their coastal proximity. Management of this class should be focussed on the biodiversity of the limestone pavement, and this is outlined in Section 6.2.4.

The non-native Western Red Cedar was present on two of the limestone pavements (Farrar’s Allotment and Underlaid Wood) in 2008 when the survey was undertaken. Removal of this species would likely to be of benefit to the biodiversity of these pavements for reasons outlined in Section 6.2.5.3.

Deer grazing has affected the wooded Group 8 limestone pavements in Morecambe Bay. Management to control deer population is outlined in Section 6.2.3.5.

6.3.6 Group 4 - A mossy, densely vegetated woodland limestone pavement group

Analysis of Group 4 shows that these wooded limestone pavements are the most densely vegetated of the groups, having the highest number of moss species and the largest percentage of vegetation on the clints. Differences between Group 4 and the 'classic wooded limestone pavement' class (Group 8) are subtle, with both groups aggregating to CVS class 35 i.e. 'Diverse base rich woodland/hedges' (Bunce *et al.*, 1999). One notable difference between the groups is the high abundance of Sycamore (*Acer pseudoplatanus*) on Group 4 limestone pavements. Sycamore grows prolifically and has large leaves which it sheds annually and this may account for the high Ellenberg fertility scores and lower light indicators in Group 4 (see Figure 6-5 in the previous chapter).

Management of Group 4 should therefore follow the same guidelines for maximising biodiversity on wooded limestone pavement as outlined in Section 6.2.4. In addition, although Sycamore is not considered a negative species *per se*, control of Sycamore on these limestone pavements may be of benefit by reducing shading and soil eutrophication from autumn leaf fall.

Research into the history of the management of the wooded limestone pavements in Group 4 suggests that they may have been subject to disturbance through commercial coppicing operations and conifer planting to support various industries in the past. Oxenber and Bastow Wood provided wood for fuel for the lead mining industry (Raistrick & Jennings, 1965) and for the local lime kilns (White, 2006). Interpretation boards at Trowbarrow Quarry bear reference to the production of charcoal for lime making while Dalton Woods and Hampsfield Wood were used as plantations in the 1960s by the Forestry Commission (B. Grayson, 11th November 2010, pers. comm.). The historical management of these sites may have affected the plant communities on limestone pavements in Group 4 leading to a classification that is a 'transitional' group.

Conservation management of Group 4 limestone pavements should firstly establish the prime objectives for the site. This includes considering the history of the site, presence of non-native species and management needs of target species. Some of the limestone pavements in this group e.g. Oxenber and Dalton Crags have large open pavement areas which with sympathetic management may have the potential to increase their richness in those limestone pavement species associated with open sites (see Section 6.2.3). Denser, more wooded Group 4 limestone pavements such as Trowbarrow and Hampsfield Wood would benefit from woodland management techniques outlined in Section 6.2.4.

6.4 Summary of Limestone Pavement Management by Holistic Classification

This chapter aimed to summarise the latest research into management techniques employed on limestone pavements and to link best practise conservation management to the holistic classes established through this research. A flowchart is presented in Figure 6-12, summarising the recommendations made.

Van Rensburg, Kelley and Yadav (2009) observe that "*the discovery of the best scientific practices in terms of farming for conservation does not guarantee its adoption and hence cannot promise the achievement of desirable environmental outcomes. Despite its greater overall benefits to society, the lack of proper incentives to farmers could lead to the adoption of suboptimal practices. Hence it is important to understand how market structures as well as rural and environmental policies influence decisions taken by farmers and why they frequently fail to protect biodiversity and other non-market values*".

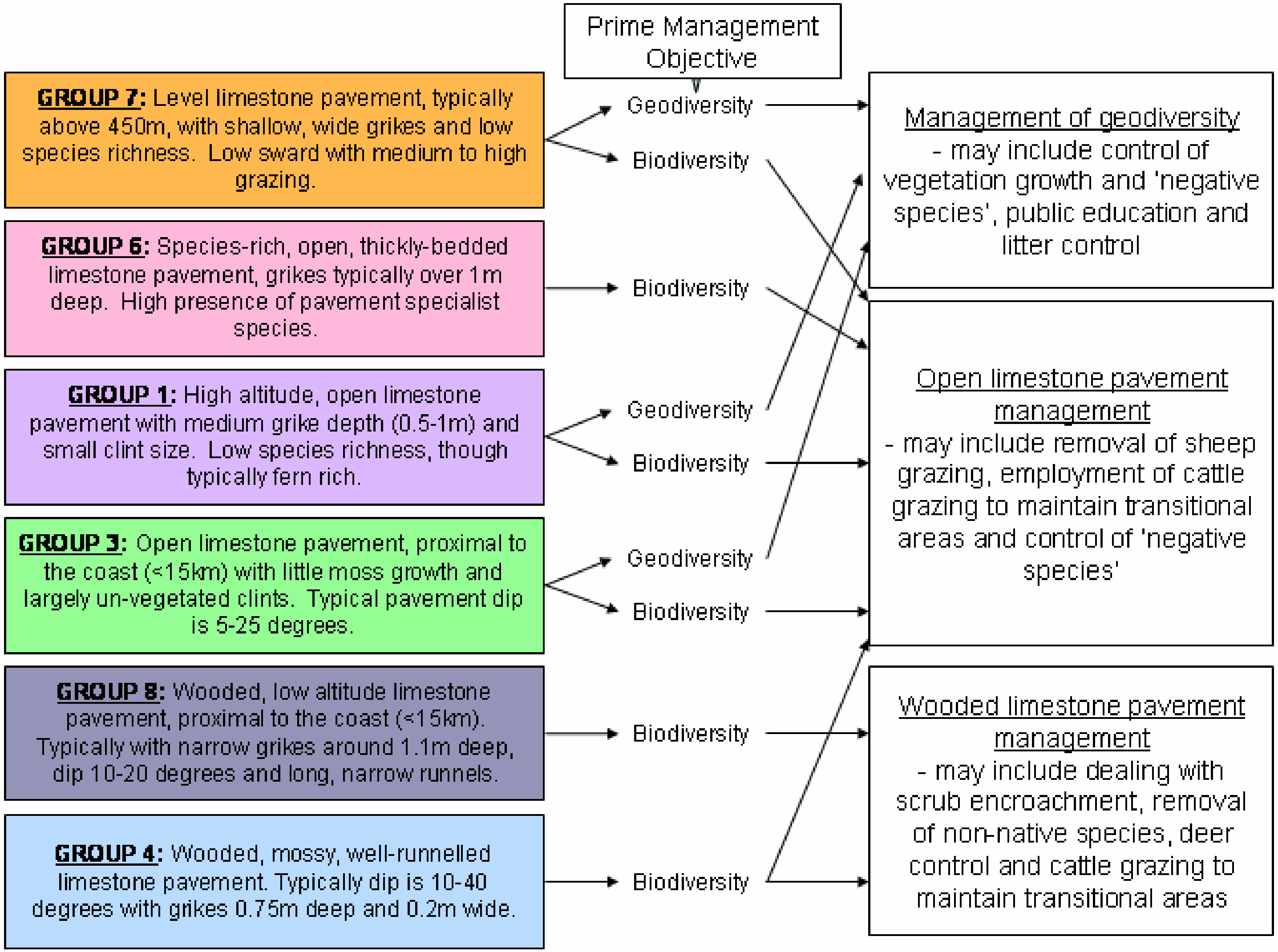

Figure 6-12: Flowchart linking holistic classes with potential management strategies.

7 MOLLUSCS AND LIMESTONE PAVEMENT IN N. YORKSHIRE

7.1 Introduction

This chapter describes a project investigating mollusc populations found on limestone pavement habitats. It was carried out as a case study piloting the holistic classification of limestone pavements, described in Chapter 5, which analysed the geodiversity and biodiversity of 46 limestone pavements across the North West of England and North Wales. Eleven of these limestone pavements within the Yorkshire area were surveyed for their mollusc populations and were analysed together with the data collected for the wider limestone pavement classification.

The aim of studying mollusca on limestone pavements was to address the current dearth of published research on the zoological aspects of this habitat (Webb & Glading, 1998) and, more specifically, the mollusca assemblages found there (Deacon & Burek, 1997; Swindail, 2005). By dovetailing the expertise of Adrian Norris, national non-marine recorder for the Conchological Society of Great Britain and Ireland, with data collected as part of the holistic study of limestone pavements, it was hoped to advance the understanding of limestone pavement as habitats for mollusca. The second aim was to pilot the holistic classification of limestone pavements, investigating the relationships between molluscs and the different classes of limestone pavement.

The association between molluscs and limestone pavements has been insufficiently researched due to a number of factors:

- Sampling in deep, narrow grikes is particularly difficult, due to the physical constraints of the environment.
- Specialist equipment is required if freshwater springs are nearby, as conditions may be marshy at the base of the grikes (A. Norris, 19th March 2008, pers. comm.).

- Lack of taxonomic expertise is a third factor limiting research in this subject and has been cited as an issue, particularly in undergraduate projects (Lloyd-Jones, 2001; Nicholls, 2009; Swindail, 2005).

In general, calcareous habitats are rich sites for biodiversity and grikes offer sheltered refuges with their own micro-climates which are highly suitable for mollusc populations (Burek & Legg, 1999b; Inman, 2000; Webb & Glading, 1998). Wooded pavements, in particular, provide mossy shelters and the presence of certain species can indicate an ancient woodland site (Cameron *et al.*, 2006). This has been demonstrated at Colt Park Wood, a National Nature Reserve in the Yorkshire Dales National Park, which hosts rich and diverse mollusc populations. It was designated in 1962 and is one of the few limestone pavements that has detailed records collected over many years of the mollusc species present (Backmeroff, 1989; Stratton, n.d.).

Mollusc assemblages on open limestone pavements tend to be generalist species, as habitat conditions are difficult. There is both a lack of their preferred foodstuffs (dead leaves, lichen, fungi, algae and stressed plants or plants such as seedlings which contain little chlorophyll) and a lack of mossy cushions which offer shelter. Molluscs only eat fresh plants when they are unable to obtain their normal food types as they have difficulty digesting chlorophyll (A. Norris, 19th March 2008. pers. comm.).

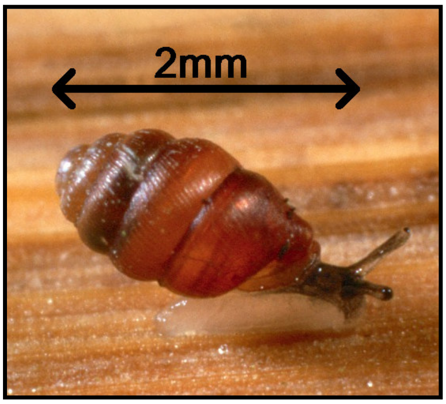

Figure 7-1: *Vertigo angustior*, image copyright D.G. Rands.

Research on Welsh limestone pavements, conducted at the University of Chester, indicated that limestone pavements offering a mixed habitat with wooded and open areas suit the most diverse range of mollusc species (Swindail, 2005). Swindail recommended further research which should include the sampling of a wider range of limestone pavement sites.

One rare snail species, *Vertigo angustior* (Jeffreys, 1830) (Figure 7-1), has an association with limestone pavement (Killeen, 1997). This species is classified as Vulnerable on the IUCN Red List, Endangered on the UK's Red

List and is included in Annex II of the EC Habitats Directive (UK BAP, 2008). This species is approximately 2mm long and Gait Barrows in Lancashire has one of the largest known populations in the UK, with densities of around 1500 individuals/m^2. It lives amongst moss and litter in the transition zone between open pavement areas and areas of woodland/scrub. Sampling for this species is complex, involving removal of the vegetation layer, drying of this material, sieving and examination under a microscope to estimate species numbers. Concern has been expressed over the destructive nature of this sampling as the habitat is quite a limited one, and monitoring is restricted to avoid damage to populations (Killeen, 1997).

During fieldwork for this research, the author observed a distinct white banding on the limestone pavement around the margins of some clints and solution pans. This observation is outlined in this chapter and causative factors are briefly discussed in relation to whether mollusc grazing may contribute to these white margins (Willis & Norris, 2009). Lichen-free edges are cited as being suggestive of vegetation contracting on limestone pavements as part of the vegetation successional processes, particularly linked with sheep grazing (Webb & Glading, 1998). Full examination of this observation was not feasible within the time constraints of this study, but merited brief mention as part of the holistic examination of limestone pavement, and would provide an interesting topic for future investigation.

The overall aim of this aspect of the research was, therefore, to examine populations of mollusc species on limestone pavements in order to investigate the relationships between mollusc species and different types of limestone pavement. Of specific interest was the question of whether there was a particular mollusc species assemblage associated with the limestone pavement holistic classes and whether the presence or absence of any individual species could be linked to the holistic limestone pavement classification.

7.2 Methodology

The approach to the development of the methodology was to ensure that sampling for mollusc species followed the same rationale as that used when sampling plant communities on the limestone pavements (see Chapter 2). Identical geographical boundaries for each limestone pavement were therefore sampled, using detailed mapping and GPS, and species search methods were replicated between limestone pavement stands. This ensured that population studies could be compared across sites and relationships between the mollusc and plant communities could be examined.

Limestone pavement selection for the mollusc study was based on a Yorkshire sub-set of those limestone pavements randomly selected for the holistic classification of limestone pavement research, as detailed in Chapter 2 (Figure 7-2). Pavements were visited together by the author and the conchologist to ensure that the pavement areas searched for molluscs matched the physical boundaries used to collect the environmental and plant data.

Determining the nature of mollusc communities on limestone pavement does not lend itself to random quadrat sampling, as molluscs are rarely distributed randomly on any site (Cameron, 1982), and particularly on limestone pavement with its clints and grikes. Consequently qualitative sampling (visual search) was the method chosen, with the addition of sieving through leaf litter in wooded areas to examine the substrate for small and cryptic species. Where searchers are skilled, as in this case, and full site inventories are not the prime aim, visual searching is deemed suitable (Cameron & Pokryszko, 2005). Additionally, all limestone pavements in England are habitats protected by Limestone Pavement Orders (LPOs), under Section 34 of the Wildlife and Countryside Act (1981, amended 1985) (HMSO, 1981). Quantitative sampling methods involve the removal of quantities of substrate which would be destructive to the habitat, so was not incorporated into this research.

A robust visual species search was conducted within the defined pavement boundary by the conchologist, replicating search effort across all stands visited. Nomenclature followed Anderson’s non-marine Mollusca of Britain and Ireland (Anderson, 2005), updated in 2008 (Conchological Society of Great Britain & Ireland, 2008).

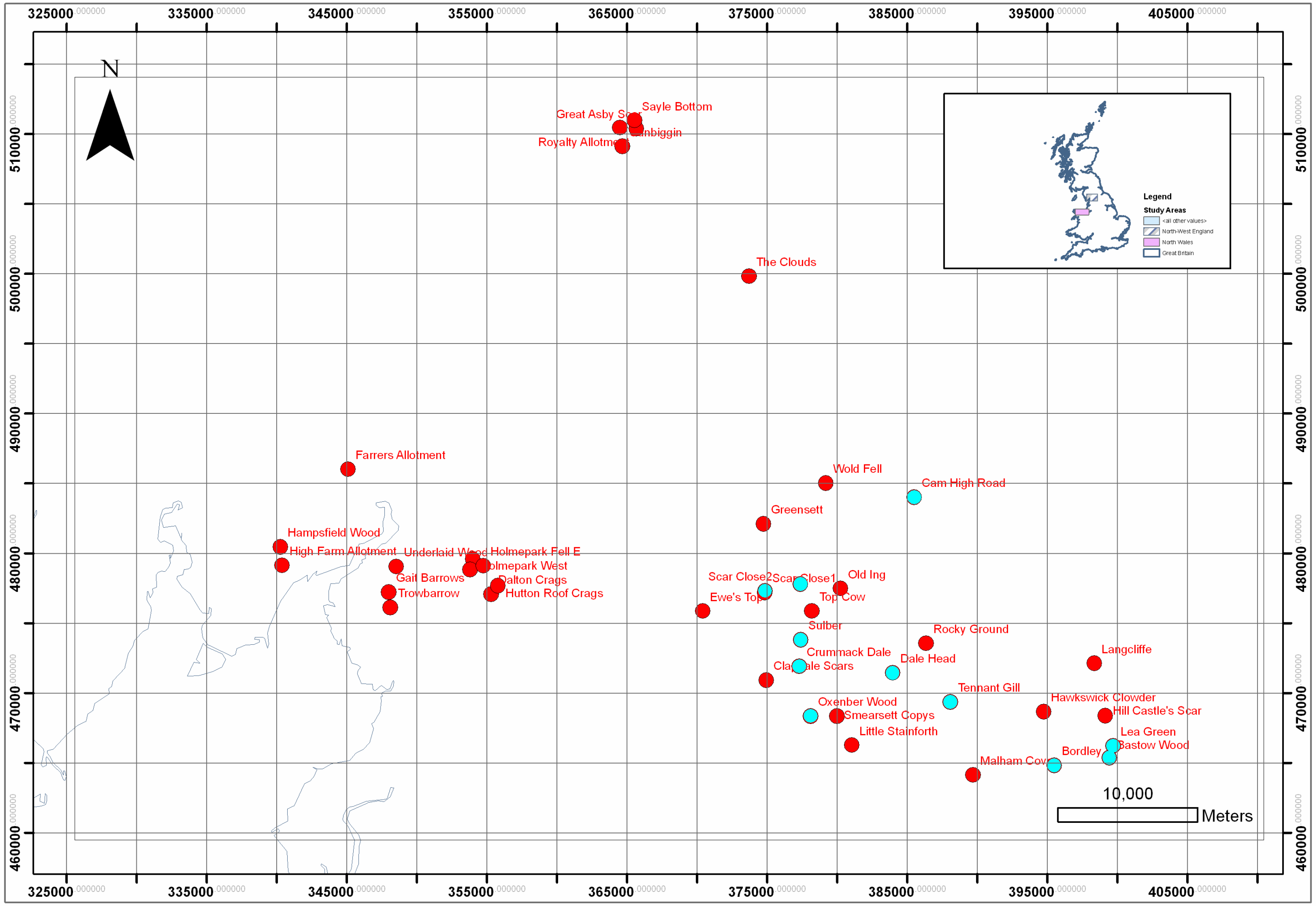

Figure 7-2: Location of the 40 limestone pavements that were assessed in the northern study area (see legend), marked by dots. The 11 Yorkshire sites included in the mollusc research are indicated in blue. © Crown copyright/database right 2007. An ordnance Survey/EDINA supplied service.

Figure 7-3: Adrian Norris, right of picture.

Snail populations are generally observed to have seasonal variability with numbers at their lowest during winter (Cameron & Pokryszko, 2005). Contrary to this, however, a small study of mollusc communities conducted at the University of Chester on Y Taranau limestone pavement concluded that there was no statistical variation in mollusc populations between winter and summer recordings (Swindail, 2005). The research described here was conducted during spring, summer and autumn, avoiding the winter months both to minimise seasonal influence and for health and safety reasons. For full survey dates see Appendix K.

Analysis was carried out using a statistical software package specifically designed for analysis of data arising in community ecology, PC-ORD (McCune & Grace, 2002) comparing mollusc species data with the geodiversity and biodiversity datasets from the limestone pavement analysis undertaken in 2007 and 2008 and outlined in detail in previous chapters.

7.3 Results

7.3.1 Mollusc Species Identified

Several nationally important snails were identified on some of the 11 Yorkshire limestone pavements visited. These included an ancient woodland species, *Cochlodina laminata* (Montagu, 1803) (Fig. 7-4), a mountain limestone species, *Clausilia dubia suttoni* (Westerlund, 1881) (Fig. 7-5) and *Helicigona lapicida* (Linnaeus, 1758) (Fig. 7-6), an open crag and limestone wall species.

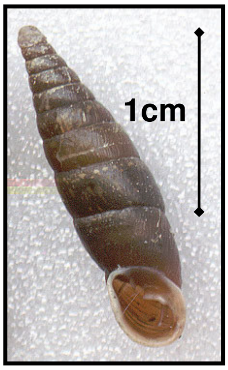

Fig. 7-4: ***Cochlodina laminata***

Fig. 7-5: ***Clausilia dubia suttoni***

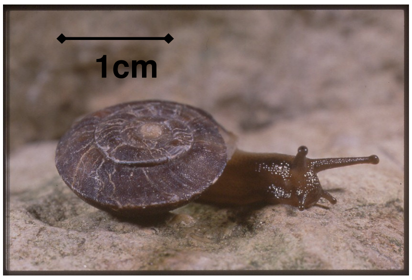

Fig. 7-6: ***Helicigonia lapicidia***

Figure 7-7: Scar Close limestone pavement illustrating the mixed nature of the habitat types, deep grikes and large un-dissected clints present at the National Nature Reserve (NNR).

A full list of species found on each pavement can be found in Appendix K. The richest site, with 36 mollusc species, was Scar Close (IBSCAR, pictured in Figure 7-7), a site with mixed habitats including open, scrubby and wooded pavement areas. This pavement is a National Nature Reserve and has been managed for its rare plant species since the 1970s. Colt Park Wood (IBCOLT, Figure 7-8) was also species-rich, with 30 species found there. This pavement is densely wooded and has been undisturbed since the 1960s and also houses several rare plant species.

Figure 7-8: Colt Park Wood, part of Ingleborough NNR, pictured here in May 2007.

Figure 7-9: Cam High Road, Coverdale, illustrating the small, well-dissected and laminate nature of the clints and shallow grassy grikes.

Conversely, the lowest species numbers were found at Cam High Road (YORCAM, Figure 7-9) with only 13 species recorded there.

7.3.2 Mollusc Species Richness and Diversity

Correlation scores give similar results for both richness and diversity of mollusc species on 11 limestone pavements and are presented in Table 7-1. The most significant correlation is between mollusc species richness and mean depth of grikes on limestone pavement (p=0.007) with greater species richness found on pavements with deeper grikes.

Significant correlation between plant species richness and mollusc species richness and diversity (p=0.019 and p=0.025 respectively) points to a close relationship between flora and molluscs on limestone pavements.

Table 7-1: Pearson correlation of mollusc species richness and diversity against 16 measured limestone pavement variables. ** represents significance at the 0.01 level (2-tailed) and * significance at the 0.05 level (2-tailed), n=11

		Mean grike width	Mean grike depth	Mean clint width	Runnel freq	Mean soil depth	Dip	Altitude	Min sward height
Mollusc Species Richness (S)	Pearson Correlation	.259	.757**	.646*	.233	.140	.035	-.499	.266
Mollusc Species Diversity (H)	Pearson Correlation	.245	.715*	.597	.349	.160	.135	-.607*	.319

		Dist. to Fault	Wind speed	AB species	Prox-imity to neigh-bour	Area (sq. m)	Litter	Plant richness	Frost per annum
Mollusc Species Richness (S)	Pearson Correlation	-.046	-.431	-.409	-.409	.688*	-.087	.690*	-.298
Mollusc Species Diversity (H)	Pearson Correlation	-.175	-.511	-.508	-.508	.596	-.015	.666*	-.420

Examining goodness of fit shows mean grike depth accounts for 57% of the variation in mollusc species richness on limestone pavements. ANOVA of the regression tells us that grike depth is a statistically significant predictor of species richness on limestone pavement stands (Pearson, F=12.07, p=0.007, n=11).

There were two significant variables which account for almost three-quarters of the mollusc species diversity on limestone pavement. Grike depth accounts for 51% of the variance in species diversity and with altitude accounts for 74% of the variance. Again, ANOVA of the regression tells us that both grike depth (1) and the combination of grike depth and altitude (2) were statistically significant predictors of species diversity on limestone pavement stands (Pearson, (1) $F = 9.43$, $p=0.013$ and (2) $F = 11.19$, $p=0.005$, $n=11$).

Mollusc species richness and diversity was positively correlated with grike depth, indicating that deeper grikes host more mollusc species and in greater densities. Altitude has a negative relationship with mollusc species diversity so significantly fewer mollusc species can be found on the higher pavement stands.

7.3.3 Analysis using Limestone Pavement Classification

The holistic analysis of limestone pavement geodiversity and biodiversity was conducted in Chapter 5, detailing the steps used to incorporate the analyses from Chapters 3 and 4 into a holistic limestone pavement classification, summarised in Table 7-2. These groups were used to analyse the mollusc data in relation to the holistic limestone pavement classification, and the results of this analysis are presented in the following sections.

Table 7-2: Summary of the holistic limestone pavement classification (from Chapter 5) for the Yorkshire limestone pavements. Colt Park Wood was unclassifiable, forming a group on its own (Group 5).

Group	Colour Code	Description
1		A high altitude, open pavement group with mean grike depth 0.5 to 1m and low plant species richness. Includes Crummack Dale (IBCRUM) and Sulber (IBSUL).
4		A mossy, densely vegetated woodland limestone pavement group. Includes Oxenber Wood (KWPOX) and Bastow Wood (MACBW) limestone pavements.
5		Colt Park (IBCOLT) limestone pavement only.
6		A high altitude, level, species-rich, thickly-bedded (>0.6m) open pavement group. Includes Tennant Gill (MACTG), Dale Head (KWPDH) and Scar Close (IBSCAR).
7		A high level (typically over 450m), shallow and wide grike group (grike >0.2m wide) with heavy sheep grazing intensity. Includes Bordley (MACBOR), Lea Green (MACLG) and Cam High Road (YORCAM) part of the Yoredale Group.

It was found that *H. lapicida lapicida* had a significant correlation with Group 7, the high altitude, wide grike, high grazing and low plant species richness group. Two species had a significant negative correlation with each other, *C. laminata* and *C. dubia suttoni*. *C. laminata* is an ancient wood indicator whereas *C. dubia* is a limestone/mountain relic species. *C. laminata* was mainly associated with Group 4, the wooded group, while *C. dubia* was present on more Group 6 pavements (species-rich, thick-bedded, herb abundant pavements).

Table 7-3 analyses the relationships between mollusc assemblages on the 11 Yorkshire limestone pavements and the four limestone pavement groups. Colt Park Wood was not incorporated in this analysis as it proved unclassifiable in the holistic classification (Chapter 5) and was therefore removed from the analysis to prevent skewing (Kent & Coker, 1992; McCune & Grace, 2002). There were no significant differences in species richness, evenness or diversity either between or within the limestone pavement groups.

Table 7-3: ANOVA of richness (S), evenness (E) and diversity (H) with limestone pavement classification.

		Sum of Squares	df	Mean Square	F	Sig.
S	Between Groups	188.348	3	62.783	1.157	.391
	Within Groups	379.833	7	54.262		
	Total	568.182	10			
E	Between Groups	.000	3	.000	.009	.999
	Within Groups	.002	7	.000		
	Total	.002	10			
H	Between Groups	.430	3	.143	1.249	.362
	Within Groups	.804	7	.115		
	Total	1.234	10			

7.3.4 Indicator Species Analysis

The indicator species analysis presented in Table 7-4 was used in order to detect and describe the value of different species in indicating certain environmental conditions (McCune & Grace, 2002). It is a method which combines information on the concentration of species abundance in a particular group, with the faithfulness of occurrence of species in a particular group (Dufrene & Legendre, 1997).

The p-value in Table 7-4 was based on the proportion of randomised trials with indicator value equal to or exceeding the observed indicator value. It should be noted that species with only one or two occurrences will never yield an indicator stronger than expected by chance, as the likelihood of all the occurrences falling in one group is very high (McCune & Grace, 2002). There were no significant p-values in the indicator analysis which was due to the small sample size, but this analysis is suggestive of group and mollusc species relationships.

Table 7-4: Monte Carlo test of significance of observed maximum indicator value (IV) for each species, based on 4999 randomisations. Those species with a relatively high observed indicator value have been emboldened suggesting which species were most indicative of particular limestone pavement groups. Full species names in Appendix K.

Abbrev. species name	Prime Group Membership	Observed Indicator Value (IV)	IV from randomised groups		
			Mean	s.d.	p value
Carytrid	**1**	**52.2**	**39.1**	**18.42**	**0.2224**
Laurcyli	1	28.2	28.6	0.79	0.6637
Nesohamm	1	26.1	39	18.2	0.7602
Oxycalli	1	28.6	29.4	0.86	1
Puncpygm	**1**	**50**	**39.9**	**8.16**	**0.3935**
Pyraumbi	1	28.6	27.8	0.62	0.1308
Trocstri	1	33.3	35.8	1.69	1
Vertpygm	1	30	34.9	20.17	0.7123
Vitrsubr	1	47.4	38.3	7.4	0.1362
Acanacul	4	30	34.4	19.82	0.7083
Aegoniti	4	16.7	37.2	20.36	0.9374
Aegopura	**4**	**71.4**	**40.7**	**18.84**	**0.1344**
Ariaarbu	**4**	**60**	**37.6**	**17.74**	**0.1848**
Arioater	4	35.3	34.9	4.05	0.3657
Ariodist	**4**	**50**	**40**	**8.18**	**0.3977**
Cepanemo	**4**	**60**	**37.2**	**17.63**	**0.2216**
Claubide	**4**	**60**	**37.2**	**17.63**	**0.2216**
Cochlub1	4	35.3	34	3.65	0.5481
Cochlub2	**4**	**54.5**	**39.7**	**11.74**	**0.1316**
Cochlami	**4**	**50**	**39.9**	**8.17**	**0.3953**
Deroreti	4	41.4	35.8	4.51	0.1558
Merdobsc	4	46.2	38.1	13.47	0.5487
Oxyccell	**4**	**50**	**38.9**	**7.78**	**0.0978**
Trochisp	**4**	**54.5**	**38.6**	**14**	**0.1828**
Vitrpell	4	25	36.6	20.05	0.7043
Abidseca	6	33.3	40.1	8.2	1
Acicfusc	6	33.3	40.1	8.2	1
Ariofasc	6	33.3	40.1	8.2	1
Ariosubf	6	16.7	35.3	20.59	1

Abbrev. species name	Prime Group Membership	Observed Indicator Value (IV)	IV from randomised groups Mean	s.d.	p value
Carymini	6	22.2	37	20.61	0.7347
Cepahort	6	33.3	40	8.19	1
Claudubi	6	37.5	35.1	1.95	0.1652
Coluaspe	6	33.3	40.1	8.2	1
Colueden	6	33.3	40.1	8.2	1
Derolaev	6	33.3	40.1	8.2	1
Discrotu	6	28.6	28.6	0.7	0.6705
Eucofulv	6	48.5	36.6	19.89	0.2683
Galbtrun	6	33.3	40.1	8.2	1
Pisicase	6	33.3	40.1	8.2	1
Vallexce	6	38.1	35.6	19.74	0.4899
Vertsubs	6	33.3	40.1	8.2	1
Vitrcont	6	28.6	27.8	0.58	0.1304
Vitrcrys	6	20.5	41.1	20.44	0.9344
Ariocirc	7	33.3	39.5	18.55	0.5883
Ariointe	7	42.4	39.2	9.02	0.4477
Helilapi	**7**	**66.7**	**35.3**	**19.42**	**0.1736**

Group 4 included Oxenber and Bastow Woods, both of which have historically remained relatively undisturbed. Mollusc assemblage at these pavements was diverse, with 24 and 25 species noted respectively. Within this group was the indicator species *C. laminata*, an ancient woodland species, locally common at Oxenber Wood (Fig. 7-4). Analysis confirmed that *H. lapicida* (Fig. 7-6) was associated with the high altitude, shallow grike limestone pavement group (Group 7). This species is uncommon and has a habitat preference for limestone rocks, crags and screes.

7.3.5 Multivariate Analysis of Mollusc Populations and Interpretation in terms of Key Environmental Factors at each Limestone Pavement

NMS using PC-ORD (McCune & Mefford, 2006) from a Sørensen (Bray-Curtis) similarity matrix of untransformed mollusc species abundance data resulted in a one axis ordination (Figure 7-10). Monte Carlo test indicated a 1-dimensional solution, after 500 iterations, which resulted in a final stress score of 25.46, indicating a relatively poor fit, likely to be related to the small datasets and the presence of two strong outliers (Cam High Road and Colt Park Wood) (Clarke, 1993; Kruskal, 1964). Interpretation therefore required caution (Clarke & Ainsworth, 1993) but bivariate correlation was used to examine the strength of the relationship between axis 1 and thirteen environmental factors.

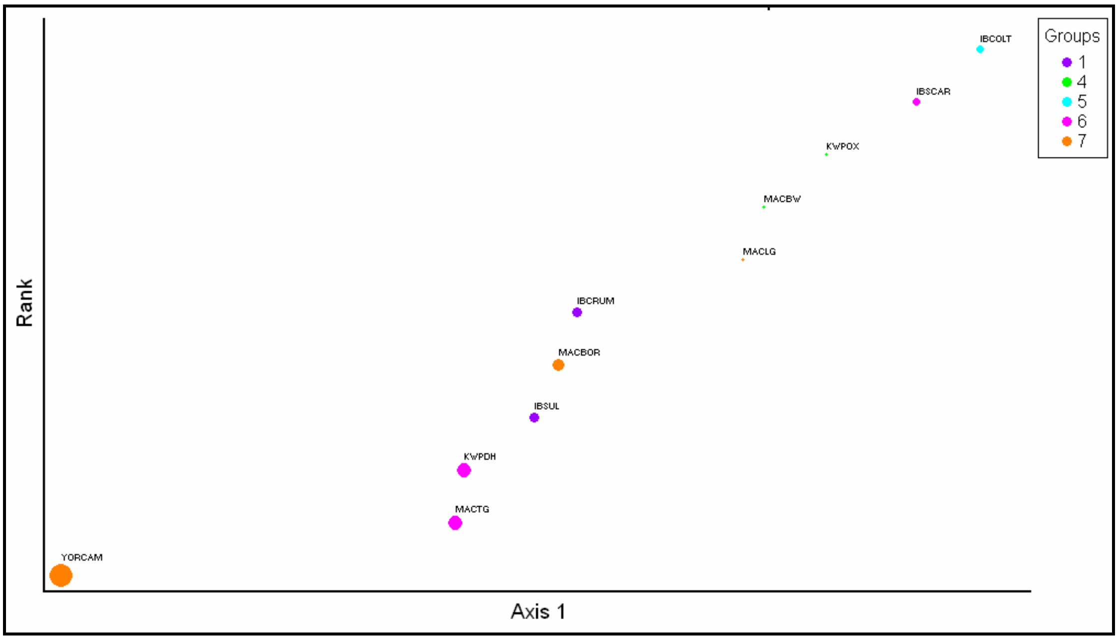

Figure 7-10: Ordination showing similarity between sites based on mollusc species abundance. Each symbol represents a limestone pavement and the colour of the symbols reflects pavement group membership (see legend and Table 7-2). Symbol size indicates the altitude of the limestone pavement with larger dots representing the higher altitudes.

A table listing correlation scores and environmental factors is presented in Table 7-5. This indicates that the prime factors driving the gradient were landscape features i.e. altitude (r=¯ 0.869) and wind exposure (r=¯ 0.765), both exhibiting a significant negative relationship with axis 1. The correlation coefficient value (r) was also notably high in relation to the mean grike depth at the limestone pavement (r=0.559) but this was not significant, as it was below the critical value of 0.576.

The relationship between plants and molluscs on these limestone pavement stands was examined further by correlating the axis scores from the PC-ORD ordination of the plant species present with those of mollusc abundance at each of the 11 limestone pavements (Table 7-6). There is a highly significant correlation between the ordination of mollusc abundance data (AXIS 1 MOLLUSC) and the third axis (AXIS 3 FLORA) from the ordination of plant data (presence-absence) on the 11 limestone pavement stands investigated (Pearson, $p<0.001$).

Table 7-5: Pearson correlation coefficients (r) between ordination axis one scores (Figure 7-10) and measured environmental factors. The critical value for r is 0.576 at p<0.05 (* indicates significance) and is 0.708 at p<0.01 (indicates significance) (n= 11, df=10) (Fowler *et al.*, 2002).**

Environmental Factors	r value
Grike width (mean)	0.112
Grike depth (mean)	0.559
Clint width (mean)	0.326
Runnel frequency	0.305
Soil depth in grikes (mean)	0.167
Pavement Dip	0.340
Altitude	¯ 0.869**
Sward height on pavement	0.480
Distance to major fault	¯ 0.485
Windspeed (mean annual)	¯ 0.765**
Presence of rare plant species	0.479
Area (sq.m.)	0.369

Table 7-6: Correlation analyses of ordination axis scores from PC-ORD. ** indicates that correlation is significant at the 0.01 level (2-tailed), n=11.

		AXIS 1 MOLLUSC	AXIS 1 FLORA	AXIS 2 FLORA	AXIS 3 FLORA
AXIS 1 MOLLUSC	Pearson Correlation	1	¯ .067	.299	¯ .885 **
AXIS 1 FLORA	Pearson Correlation	¯ .067	1	¯ .036	¯ .044
AXIS 2 FLORA	Pearson Correlation	.299	¯ .036	1	¯ .296
AXIS 3 FLORA	Pearson Correlation	¯ .885 **	¯ .044	¯ .296	1

7.4 Discussion

Grikes provide environments similar to those of woodland, protecting a wide range of plant species and collecting leaf litter, thus offering a variety of habitats for molluscs. Previous research has demonstrated that grikes exhibit micro-climates with temperatures more stable, particularly in winter (Burek & Legg, 1999b; Inman, 2000). Temperature can vary dependent on grike orientation, with north-south orientated grikes showing a marked increase in temperature range compared with east-west orientated grikes, further varying with grike depth (Burek & Legg, 1999b; Lloyd-Jones, 2001).

The research presented in this chapter has shown that deeper grikes contain the greatest mollusc species richness and diversity, mirroring results found in plant studies on limestone pavement (Silvertown, 1982; Willis *et al.*, 2009).

Limestone pavement with a mixed habitat (which includes wood, scrub and open pavement) and long-term traditional management had the greatest species diversity; findings corresponding with previous knowledge of mollusc populations (Conchological Society of Great Britain & Ireland, 2009; Kerney & Cameron, 1979).

Conditions on open, exposed pavements at higher altitudes are the least hospitable for molluscs, and species diversity is predictably reduced. This is particularly notable where grikes are shallow, affording little or no protection from the elements, as seen at Cam High Road (Figure 7-9 and Figure 7-10). This pavement is markedly dissimilar to the other pavement stands in its mollusc population. At 592m (over 150m higher than other sites), and with the shallowest grikes, relatively few mollusc species were found and it lacked the characteristic woodland species seen on other limestone pavements. The low species numbers at this site and the types of species present were indicative of the pavement's high altitude and shallow grikes.

Cam High Road is a poor quality limestone pavement that is being managed primarily for limestone grassland and sheep grazing. No woodland molluscs were found here, only generalist, rubble and grassland species; a similar picture to that observed with the plant ecology of this pavement. The lowest numbers of species were found at Cam High Road, numbering only thirteen. High levels of sheep grazing have been associated with reduced biodiversity on limestone pavement (Conway & Onslow, 1999; Smith *et al.*, 2008; Thom *et al.*, 2003). Recent research by Nicholls on Welsh limestone pavements also concluded that snail diversity was significantly greater on undamaged limestone pavement when compared with damaged pavement at the same site (Nicholls, 2009). Low mollusc species numbers at broken pavement sites such as Cam High Road and Crummack Dale (IBCRUM) suggest that that may also be the case on Yorkshire limestone pavements.

This research goes some way towards identifying which mollusc species have a relationship with particular types of limestone pavement (Table 7-4), outlining mollusc indicator species for four of the limestone pavement classification. Associations were not statistically significant due to the small sample sizes but are worthy of note as the assemblages presented here do give an indication of mollusc populations on different classes of limestone pavement in Yorkshire.

Figure 7-11: A number of *Pyramidula rupestris* pictured on limestone, with camera lens cap to provide scale.

During this study, incidental observations were made on the limestone pavements concerning 'white edges' evident around grike margins (Figure 7-12). Literature review and discussions with experts in this field of study have suggested a number of possible theories for the cause of this. They include mollusc grazing on lichens, vegetation retreat where this is seen around vegetated solution cups (after Jones, 1965), a fungal activity on the lichen, or insect grazing (J. Newton, 2nd April 2008; A. Norris, 27th November 2009; and S. Parr, 30th March 2008; pers. comms.).

Figure 7-12: White edges can be clearly seen on grike margins at Hutton Roof limestone pavement, Lancs.

Pyramidula rupestris is a tiny snail (2.5-3mm) that can occur in vast numbers on dry limestone rocks that are un-shaded by trees. It hides in crevices or on the undersides of rocks, emerging at night or in damp weather to graze on lichens and algae. Newton reports that it has been lost from S.E. England, possibly as a result of Sulphur Dioxide (SO_2) damage to lichens. She states "I am not aware of any work done on its impact on vegetation of the rocks, but it can occur in such numbers that I imagine it must have an impact" (J. Newton, 2nd April 2008. pers. comm.).

Similar observations were photographed by Parr (Figure 7-13) during a visit to limestone pavements in Öland, Sweden. Parr noted that there were distinct similarities between the white edge effect at the two sites (S. Parr, 30th March 2008, pers. comm.).

Figure 7-13: Parr's 2006 picture of Öland limestone pavements, with similar 'white edges' to the grike margins.

Norris is of the opinion that "the damage to the lichens looks like grazing damage". In his view the damage can be done by several different organisms. Slugs and some large snails are known to graze close to their hiding places and some species can be very difficult to find in daylight. He added that "some small insect orders are also very common in this type of habitat and they are known to graze on lichens and if the numbers are high enough can do damage of this type". It is his opinion that grazing by slugs at night causes this white banding phenomenon (Willis & Norris, 2009). Further investigation of this observation would be interesting, but was beyond the remit of this research.

7.5 Summary of Molluscs Analysis

This study established significant links between the geodiversity of limestone pavements and their mollusc populations, illustrating clearly that geodiversity underpins biodiversity (Burek, 2001). Patterns of mollusc species have been identified relating to the limestone pavement holistic classification which was derived from geodiversity and biodiversity variables. Key drivers for mollusca communities echo those of plant species on limestone pavement, namely altitude, exposure and grike depth. Further work is indicated, to extend this work beyond the limestone pavements of Yorkshire, including an investigation to identify which causal factors create the white strips around limestone pavement grike margins and solution cups.

8 DISCUSSION AND CONCLUSIONS

8.1 Introduction

This chapter discusses the merits and limitations of the holistic examination of limestone pavements across North West England and North Wales. It highlights the outcomes from the analysis of the geodiversity and biodiversity of the 46 limestone pavement stands studied, and considers the validity of the process of holistic classification. The chapter concludes by reflecting on how the application of the classification will impact management of the sites and it outlines recommendations for further work.

The overall aim of this study has been to produce a holistic classification of limestone pavements based on both geodiversity and biodiversity. The objectives included:

- Review of current limestone pavement assessment techniques, classifications, management practises and conservation legislation.
- Establishment of a robust, consistent methodology to measure multiple factors during fieldwork.
- Detailed analysis of the geodiversity and biodiversity of a sample of limestone pavements randomly selected from North West England and North Wales.
- Combination of these analyses in order to holistically classify limestone pavements.
- Linking best practise conservation management objectives to the new holistic classification system.
- Trialling the classification considering molluscs as a case study.

8.2 Methods and Approach

The review of the literature concerning the assessment of limestone pavement habitats outlined in Chapter 1 indicated that geodiversity and biodiversity measurement on limestone pavements have historically been considered independently. During the course of this research it was therefore necessary to produce a collective, multidisciplinary methodology in order to provide the detailed and holistic assessment of limestone pavements required to meet the aims of the study. In examining the way the research should be conducted consideration was given to the use of remotely sensed images and aerial photography, but both have their limitations in wooded limestone pavement habitats. Thus the research used a primarily field based protocol which was thorough in its approach. A detailed examination was conducted of a stratified random sample selected from the full range of limestone pavements across North West England and North Wales, and this was outlined in Chapter 2.

The methodology used in this study was unique in that it combined traditional, standardised assessments with new pioneering techniques in order to create a full picture of each limestone pavement habitat. The limitation of the functional field-based approach was that the amount of equipment that could be physically carried was restricted, impacting on some elements of the research. An example of this was the measurement of the clint edge profile which may have produced more precise results using specialised equipment, but this was too large to be included in the fieldwork pack.

The limestone pavement sampling across the study region was stratified into geographical groups to ensure a representative sample was taken from each area. This built on the monolithic work conducted by Ward and Evans (1975) and enabled a cross section of limestone pavements to be examined across North West England and North Wales. 46 sites were assessed i.e. approximately 10% of limestone pavements in this geographical area (Deacon & Burek, 1997; S. Campbell, 1st November 2006, pers. comm.; S. Webb, 13th February 2007, pers. comm.; Ward and Evans, 1975), and representing the largest academic study of this habitat since Ward and Evans floral analysis in the 1970s. Where Ward and Evans sites have been re-assessed it also provides the opportunity to compare changes in the plant communities on the limestone pavements over the past thirty years, particularly valuable where there have been alterations to management during that time.

The methods for assessment of soil character provided a summary picture of the pH, texture and colour of soils taken from random grike samples (Chapter

3). Soils were predominantly neutral to basic (pH 7-7.5) silty loams, with mean depth ranging from 40-453.3mm. Soil depth was found to have a significant negative relationship with sward height, a surrogate measure for grazing pressure. This suggests that the presence of grazing animals adds organic matter to the soils in the grikes. Evidence of this was the numerous scats observed on a number of the limestone pavements studied (see Chapter 4, Figure 4-9). In this research high grazing was identified as having a negative impact on the biodiversity of the limestone pavements in terms of species richness and presence of limestone specialist plant species (Chapter 4). These results correspond with the findings of Smith, Sanderson, Rushton, Shiel, Grayson, Millward, Wilmore, Woodward, Bevan and Wainwright (2008) in their research related to the Limestone Country Project in the Yorkshire Dales National Park. The addition of organic matter impacts the soil character and soil diversity can be lost as a result (Burek & Conway, 2000b; Van Beynen & Townsend, 2005). Eutrophication will also result in deterioration in the classic rendzina soils that are associated with limestone pavements (Conway, 2007).

A negative association was identified between the height of emergent species and the depth of soil in the grikes. Wooded limestone pavement had the highest mean emergent height, but Group 8, the 'classic' wooded limestone pavement group had the shallowest soils. This may be related to the narrow grikes within this group but possibly also to other factors such as depth and form of glacial deposition or degree of glacial scour, both factors which would require further investigation in order to draw any firm conclusions.

Soil profiles examined during field tests indicated marked variations in single samples, and it became apparent that the soil analysis techniques lacked sensitivity. A method that incorporated detailed analysis of each soil horizon in the profiles, including soil chemistry and organic content, would have enhanced this study and should be added to future investigations. Detailed examination of the relationships between the different soil types found in karst regions such as the shallow rendzina soils, glacial drift or loess, and the functional holistic limestone classification would prove an interesting further study.

Three aspects of the methodology that were used during this research have the potential to contribute to the future monitoring of limestone pavements. These are:

- **The modified Pavement Formation Assessment (PFA)** - This research proposes that the PFA may be a useful tool for monitoring the intactness of the geodiversity of limestone pavements (Appendix H). Its strength is that it is quick to use and thus it can be applied by people from different disciplinary backgrounds (see Section 8.3 for further discussion of the PFA).
- **Recording of the modal tallest emergent species** - Recording the five tallest emergent species on each limestone pavement and calculating the mode may also provide an additional tool to be used to indicate unsustainable grazing management at a site. Current monitoring under the Upland Vegetation Condition Assessment requires an estimation of vegetation composition and includes targets for less-favoured species such as Nettle, Dock and Ragwort (English Nature, n.d.). Using this new tool could provide an easier, quicker method of conducting this monitoring.
- **Line Intercept Sampling (LIS)** - Use of the LIS technique encapsulated a detailed combined picture of the geomorphology of 10m of the limestone pavement and its vegetation composition. This procedure had not previously been used in the assessment of this habitat and it provided a key method for relating geodiversity and biodiversity on a micro-scale in order to compare limestone pavements. This technique would also lend itself to modelling in future research projects.

8.3 Geodiversity of Limestone Pavements

Geodiversity was examined at both macro- and micro-scales in the course of this investigation. Goldie (1976) stated that structural geology impacts morphometry as it creates the overall patterns of weakness in the limestone which are then exploited by solution. In this research the key influences on limestone pavement geodiversity were found to be lithology, proximity to structural fault and altitude, as discussed in Chapter 3, and this confirms previous authors' work including Williams (1966), Goldie (1976), and Goldie and Cox (2000).

The limestone pavements were found to vary depending on their stratigraphy; with the Carboniferous Supergroup limestones notably thicker than those of the Yoredale Group limestones. Differences were also evident in their lithologies with the Yoredale Group, comprising thin limestones with mudstones and thin sandstones, producing limestone pavements with shallow, wide grikes and typically smaller clints and with greater fossil interest.

The proximity of a limestone pavement to a major structural fault had a direct relationship not only with the limestone pavement dip, but also with the size of the clints and the amount of mineralisation. Limestone pavement that was closer to a faultline demonstrated a greater dip, smaller clints and an increase in visible calcite vein intrusion. This result is as expected, as rock becomes increasingly distorted with greater tectonic influence, because of the pressures exerted on it (Burek & Conway, 2000b). Limestone is a mechanically competent rock which fractures rather than deforming, as a response to pressure. This gives rise to increased points of weakness which are then exploited by solutional processes, or subject to secondary mineralisation (Sparks, 1971).

Climate had a close relationship with the altitude of the limestone pavements, with the higher sites experiencing significantly more frost days, greater precipitation and higher average wind speeds. The moderating effect of the coast on climate also proved a significant distinction between the limestone pavements. Estimates of climate were based on averages calculated by modelling (Department of Energy and Climate Change (DECC), 2010; Met. Office, 2009) so were not specific to the microclimates or individual topographical variations that have been previously identified at limestone pavements (Alexander *et al.*, 2005; Silvertown, 1982, 1983). This climate data should therefore be considered as a general overarching picture of the climatic influences on the 46 limestone pavements. Closer examination of the limestone pavement microclimate and topography relating to each limestone pavement group would provide valuable additional information for the future development of this holistic classification.

The influence of stratigraphy and lithology was apparent in the grike and clint metrics of the limestone pavements with the limestone pavements of the Yoredale Group having shallower grikes, smaller clints and fewer runnels. More thickly-bedded limestone pavements were associated with deeper grikes, larger clints and longer/wider runnels. This work corresponds with the observations of Sweeting (1966). Morphometric analysis revealed the same relationship that was identified by Goldie and Cox (2000) whereby average measurements in sequence were clint length (largest), clint width, grike depth with grike width the smallest. It should be noted that clint measurements were not independent, as by definition, clint length was greater than clint width.

The frequency and nature of the runnels on the limestone pavements were identified to be significantly related to grike and clint metrics. Deeper grikes were associated with longer and wider runnels, as were larger clints. Runnel frequency was also greater on limestone pavements with longer clints. Dip was positively associated with an increase in frequency of runnels on the limestone pavements and Groups 4 and 8 respectively had the greatest frequency of runnels, correlating directly with the highest degree of pavement dip. This is likely due to the catchment effect of rainfall on the clint as the surface angle of the clint, which is directly related to the bedding plane dip, will channel the water and increase the solutional erosion of the limestone. This was observed at Dalton Crags in Group 4 (Figure 8-1). The greater frequency of runnels on wooded limestone pavements confirms the role that vegetation cover, particularly acidic soil, has in runnel development on limestone pavements, as proposed by Böglii (1960) and elaborated on by Zseni, Goldie and Bárány-Kevei (2003).

In order to achieve a holistic functional grouping of limestone pavements within the confines of this study some factors could not be fully considered. Notable omissions were the effects of glacial scour and post glacial solution on the limestones, identified by Clayton (1981), Trudgill (1985b) and Goldie and Cox (2000) as being major factors controlling pavement form. Depth and recency of scour, topographical factors related to glacial erosion and deposition, and the variation in solutional weathering have a significant influence on limestone pavement development. Data describing the complexities of the interplay between these factors on the limestone pavements is described by Goldie and Cox (2000) as "generally difficult or impossible to obtain". It was therefore considered to be beyond the remit of this work which had a functional approach and focussed on field-based measurement data. Examination of the glacial and solutional histories between the holistic limestone pavement groups would prove interesting for future research.

Figure 8-1: Well-runnelled wooded limestone pavement at Dalton Crags with evidence of the 'rainfall catchment effect' on sloped clints.

This work has contributed to the functional measurement of geodiversity on limestone pavement however, in the way that it has trialled and developed a new assessment technique called the 'Pavement Formation Assessment' (PFA) (after G. Ellis, 2007). The PFA allowed each limestone pavement to be assessed based on the extent (i.e. how fragmented the limestone pavement was) and the condition (i.e. how broken up the clints were) of the pavement. Added to this was a proposed quality rating of the limestone pavement geodiversity (see Appendix H). This tool is a measure of the human impact on the limestone pavement, and added to photographic evidence, it can monitor disturbance of the limestone pavement over time. The UK-Ireland Limestone Pavement Geodiversity and Biodiversity Group have now proposed that this tool is added to the biodiversity monitoring carried out by conservation agencies (UK-Ireland Limestone Pavement Biodiversity Group, 2009). It may be considered a valuable addition to Common Standards Monitoring (CSM) techniques currently used by Country Agencies to evaluate the condition of limestone pavements.

8.4 Biodiversity of Limestone Pavements

This project aimed to provide a comprehensive record of plant communities and full species lists were compiled at each of the 46 limestone pavements visited. These will be of benefit to the conservation and monitoring of these limestone pavements. Unlike the Ward and Evans (1975) floral assessment, all higher and lower plants (except lichens) were included in the recording, including shallow grike, deep grike and moss species. This was necessary to fully assess all types of limestone pavements such as the thinly-bedded Yoredale Group as well as the heavily wooded sites such as Bastow Wood, Grassington, or Colt Park, Ingleborough.

The advantage of this approach was that inclusion of these additional species in the assessment allowed the limestone pavement classification to encompass the differences in the wooded sites, as bryophytes constitute a key element in woodlands (Averis *et al.*, 2004; Orange, 2009). Moss species were also identified as indicator species in one of the limestone pavement classes, Group 4. Mosses are very responsive to changes in atmospheric pollution and climate (Bates *et al.*, 2005), and Orange (2009) considers lower plants to have significant importance on limestone pavements. It is therefore hoped that recording them in the species lists and overall classification analysis will benefit future studies of this habitat.

This work confirms the findings of the floristic study by Ward and Evans (1975) which informed the legislative protection of floristically rich limestone pavement sites (JNCC, 1997). The ten most species-rich limestone pavements identified in this research are within NNRs or SSSIs. Ward and Evans floristic categories had weighted scores for plants based on their conservation value (Ward & Evans, 1976). Comparison of the species richness on the open pavement Group 6 with Ward and Evans floral index scores is worthy of note. Group 6 had the greatest species richness of all the groups and statistically significantly higher species richness than the other two high altitude groups (Group 1 and Group 7) incorporating the largest presence of limestone specialist species. From Ward and Evans data (1975) three pavements in Group 6 had the highest index score of 91+ (Scar Close, Top Cow and Tennant Gill) while two scored 71-90 (Dale Head and Malham Cove).

Figure 8-2: North Eastern aspect of Old Ing limestone pavement where deeper bedding planes/grikes were recorded. The abundance of Nettles indicates sub-optimal grazing management at this Group 6 limestone pavement.

Contrary to this, Old Ing had the lowest index score of less than 71, with relatively low total and rare species recorded in the current study, and grazing management at the site less than optimal (Natural England, 2010). Similarity in the species composition during TWINSPAN analysis (see Chapter 7) was the foundation that led Old Ing to be a member of Group 6, indicating that the species composition at Old Ing was most like the other Group 6 limestone pavements. This suggests that this site may have the potential to develop the richer limestone pavement species community that is present on the other pavements in Group 6 if management conditions were sympathetic. During fieldwork it was noted that bedding planes measured up to 3.2m in places at the Old Ing limestone pavement (Figure 8-2), and grikes were accordingly deeper in this area, a factor that is generally consistent with increased presence of limestone pavement specialist species where management is favourable (see Section 4.2.4).

Detailed analysis of the nature and position of substrate and vegetation on the limestone pavement was provided in the form of a Line Intercept Sample (LIS) across 10m at the centre of 44 limestone pavements in this research (n.b. no LIS was conducted on two limestone pavements, The Boncs (NWBON) and Moelfre (NWMOE) due to time constraints). Although this method is used in vegetation analysis, it is more often a technique employed in assessing marine environments (English *et al.*, 1997). The LIS provided a valuable and comparable 'window' across each limestone pavement. Analysis using the data accrued determined a statistically significant difference between the limestone pavements in relation to the abundance of vegetation on their clints. Group 4 had the highest proportion of vegetated clints and the greatest amount of vegetation across the LIS. The LIS proved to be a novel and valuable method for assessing this complex, three dimensional habitat.

This study has made a significant contribution to the understanding of the interactions between mollusc communities and limestone pavements. As a case study, 11 sites in Yorkshire were examined by an expert conchologist and the details of the molluscs identified were compared to geodiversity and other biodiversity variables from these limestone pavements (Chapter 7). Analysis showed a highly significant correlation between the ordination of mollusc abundance data and the ordination of plant data on the eleven sites investigated, suggesting that similar factors affect plant and mollusc distributions on limestone pavements. Mixed limestone pavement habitats and long-term traditional management corresponded with the greatest mollusc species diversity, which was consistent with Kerney and Cameron's (1979) descriptions of mollusc populations. Extending this research by assessing mollusc communities on limestone pavements outside the Yorkshire area would be a valuable further addition to this work.

8.5 Evaluation of the Holistic Classification

The holistic classification of limestone pavement presented in this thesis was produced from the analysis of in excess of 75 geodiversity and biodiversity variables from 43 of the 46 limestone pavements studied. Two limestone pavements were very small, namely The Boncs and Moelfre, Anglesey, and one limestone pavement, Colt Park Wood, was substantially different to the other limestone pavements (notionally forming a group on its own, Group 5) with all three proving unclassifiable.

Underpinning the TWINSPAN functional grouping were the plant communities recorded on the limestone pavements. Plants are recognised as growing in repeated patterns or communities that reflect their habitat or niche, and it is worth reiterating that it is the geodiversity that underpins these plant communities (Burek, 2001). Considering vegetation as a tool for classifying habitats has been used extensively in Britain (Averis *et al.*, 2004; Rodwell *et al.*, 2000). It is also recognised that in reality the picture is far closer to what Averis, Averis, Birks, Horsfield, Thompson and Yeo (2004) describe as "an immensely complicated multi-dimensional continuum".

The holistic limestone pavement classes created are intended to represent points of reference which can be used to meet the needs of managers in the conservation of this irreplaceable, unique habitat. Further research will enable the classification to be developed and extended.

The holistic classification was as follows:

- **GROUP 7**: A higher altitude limestone pavement group with shallow, wide grikes, typically heavily grazed.
- **GROUP 6**: A higher altitude, level, species-rich, thickly-bedded open limestone pavement group.
- **GROUP 1**: A higher altitude, open limestone pavement group with mid-range grike depth 0.5-1m and low species richness (also incorporating the two members of Group 2).
- **GROUP 3**: An open, coastal limestone pavement group with little moss growth and un-vegetated clints.
- **GROUP 8**: A lower altitude, sloping woodland limestone pavement group with Oak and Silver birch predominant.

- **GROUP 4**: A mossy, well-runnelled vegetated, woodland limestone pavement group.

Of particular interest are the two least clearly defined groups (Groups 1 and 3) that may be considered 'bucket' classes. These are the largest groups and work to investigate and develop the group characteristics may enhance this classification further.

The literature review identified several descriptions of limestone pavements that have considered 'scrubby' limestone pavement as a broad limestone pavement category (Lancashire Biodiversity Partnership, 2008; LPAG, 2003). TWINSPAN analysis of the 43 limestone pavement plant communities did not result in a limestone pavement classification that could be identified as 'scrubby'. However, emergent plant height was above mean levels in Group 3, the open, coastal limestone pavement group. Several of the group members, including Holme Park Quarry, Hutton Roof Crags and Taranau, were well vegetated with shrubs and trees. Future development of this holistic classification may consider whether Group 3 can be clarified further, and whether a 'scrubby' limestone pavement habitat can be defined from within this broad classification.

8.6 Management Guidelines

In the NMS ordination of the limestone pavements it is proposed that one of the factors defining their plant communities is a gradient of grazing intensity (see Chapter 4, Figure 4-11).

Medium and high levels of sheep grazing have been considered an impediment to the conservation of limestone pavements (Conway & Onslow, 1999; Graham *et al.*, 2007; Thom *et al.*, 2003; Williams *et al.*, 2009). The research described in this thesis confirms this proposition and contributes to evidence that increased grazing pressure reduces species richness, both for plants and molluscs. Of most concern to conservationists of this Annex I Habitat is the direct highly statistically significant relationship that was identified between sward height and the presence of rare limestone pavement specialist species. Analysis of the relationship between the classification and grazing intensity in Chapter 5 illustrated this point further, with significant differences in levels of grazing identified across the groups.

Grazing continues to be a management issue on limestone pavements and this study confirms the negative impact that over-grazing can have. Low sward height, as a surrogate for high grazing intensity, correlated significantly with both reduced plant species richness and less rare ('A' and 'B') species on limestone pavement. Examination of the relationship confirmed that 28% of the frequency of limestone pavement specialist species is explained by the height of the sward (grazing intensity). This research therefore contributes to the knowledge of farming management in relation to protection of biodiversity on limestone pavement, and provides a body of evidence for conservation managers.

The importance of the transitional zone from the limestone pavement to the surrounding habitat has been highlighted by previous authors as a valuable habitat for biodiversity including species such as Lily-of-the-valley (*Convallaria majalis*), Fingered sedge (*Carex digitata*) and the rare snail, *Vertigo angustior* (JNCC, 1997; Webb & Glading, 1998). Reviews of recent studies investigating cattle grazing, presented in Chapter 6, recommend traditional breed cattle grazing to maintain transitional areas around limestone pavement (Milligan, 2003; Smith *et al.*, 2008; Williams *et al.*, 2009). Cattle rarely go onto limestone pavement so grike species remain largely untouched, while scrub encroachment around the pavement areas is controlled (Dunford, 2001).

One of the concerns outlined in Chapter 6 of this thesis is that a cattle grazing regime is insufficient to maintain the open glades and clearings which are characteristic of wooded limestone pavements. This may become more of an issue in the future with the increased temperatures associated with climate change (Burek & York, 2009; Viles, 2003). Analysis of limestone pavements in Group 4 suggests this group may be indicative of wooded limestone pavements that are insufficiently grazed to prevent overgrowth, resulting in a loss of limestone pavement specialist species. Despite being the second most species-rich limestone pavement class, Group 4 had little presence of rare species. Soil depth in the grikes in Group 4 was also above the mean level, and over 50% deeper than Group 8. The dense mossy clints in this group had almost twice as much vegetation on them than the other wooded class, Group 8, and statistically significantly more than Groups 1, 3, 6, and 7. Build up of vegetation on clints in this instance is likely to be the result of over-shading, a consequence of under-grazing or lack of conservation management techniques.

English Nature (now Natural England) identified that some wooded limestone pavements were becoming overgrown and neglected, mirroring similar issues experienced on the Burren (Dunford, 2001), and a programme of remedial works commenced in the 1990s (Webb & Glading, 1998). The findings of this research confirm the value of this, and propose that limestone pavements that fall into Group 4 category could potentially benefit most. This thesis also challenges management practise that asserts that grazing is contra-indicated on limestone pavement, as in some instances structured and carefully timed grazing may be advantageous (see Section 6.2.4).

In general, management of limestone pavement habitats has historically had a focus on biodiversity issues and has a species-based approach. Ward and Evans (1976) suggest that protecting limestone pavements for their biodiversity will generally protect those pavements with the higher quality geodiversity too, a view corroborated by Webb (1995). This research has similar findings, as the limestone pavements that have the greatest range of specialist species (Group 6) display high quality geodiversity. However, some of the limestone pavements e.g. Group 7, do not display specialist limestone pavement flora yet they have other features of geodiversity, such as their fossil content, which merit a conservation focus. Managers should therefore take a holistic approach when setting conservation objectives on all limestone pavements, as outlined in Chapter 6.

8.7 Conclusions

This study has met the aims and objectives outlined in Chapter 1 by forming a holistic classification of limestone pavements across North West England and North Wales. The method adopted to develop the classification was presented in Chapter 2 and involved a functional, field-based approach, individually assessing a stratified random sample of limestone pavements. The methodology used has given rise to three novel techniques of limestone pavement evaluation that may be valuable additions to the monitoring of this endangered habitat. These are outlined in Chapter 2 and include:

- The Pavement Formation Assessment (PFA).
- The use of the modal emergent species to monitor unsustainable farming methods.
- Line Intercept Sampling for assessing both substrate and vegetation composition together.

Holistic examination of the limestone pavement geodiversity and biodiversity variables in Chapters 3 and 4 respectively concluded that geodiversity underpins biodiversity in terms of the drivers that affect limestone pavement form. Of the factors assessed, the key variables were found to be **lithology**, **proximity to structural fault** and **altitude**, dictating both geodiversity and biodiversity on limestone pavements. Allied to these was **human intervention**, particularly in terms of the **grazing intensity**, which significantly affects vegetation structure and composition.

The procedure involved in forming the six holistic limestone pavement groups was presented in Chapter 5. The classification comprised of a high altitude shallow-bedded group (Group 7), a deep-grike open group (Group 6), a mid-range open group (Group 1), a coastal open group (Group 3) and two wooded limestone pavement groups (Groups 8 and 4). The characteristics of the holistic classification were examined and contrasted, in terms of their geodiversity and biodiversity, and the distinction between groups was also presented in Chapter 5.

The links between conservation management and the holistic classification were outlined in Chapter 6, with details of best practise guidelines where these were available. These will provide a framework for the holistic conservation of limestone pavement habitats in the future.

Analysis of mollusc communities on a selection of the Yorkshire limestone pavements was detailed in Chapter 7, as a case study using the holistic classification, and this pioneering research offered an insight into the mollusc species associated with limestone pavements. It was concluded that factors influencing plant communities also affect species richness and diversity of molluscs on limestone pavements.

8.8 Recommendations for Further Study

Over the course of this investigation a number of aspects relating to limestone pavement geodiversity, biodiversity and their holistic classification have come to light that would warrant further investigation. These include:

- The development of the holistic classification to include limestone pavement across a wider geographical range.
- Detailed examination of soils, microclimate and micro-topography of the limestone pavements and their relationships to the limestone pavement classification.
- Investigation into the precise age of the limestone pavement.
- Research into the age of the exposure of the limestone pavements, potentially using advanced clint edge profiling techniques to estimate the degree of solutional weathering that has taken place.
- Examination of glacial scour, deposition and post glacial solution and their relationships to the limestone pavement classes.
- Studies of the fauna associated with limestone pavements including an extension of the work conducted in this thesis on relating mollusc communities to the different classes of limestone pavements.
- Developing knowledge of the lichen communities of limestone pavements including investigation of the causal effect of the ‘white edges’ observed during this research on some grike margins.
- Consideration of the effects of climate change on limestone pavements.

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APPENDICES

APPENDIX A: Details of Fieldwork

Study Code	Pavement name	Grid ref	Date(s) of fieldwork	Date of LIS	Botanist(s) present	Prior species list?
CUCLO	Fell End Clouds	SD737998	15/08/08 22/08/08	22/08/08	Sue Willis	No
CUGAS	Great Asby Scar	NY657104	09/07/08 04/08/08	04/08/08	Sue Willis	Yes
CURA	Royalty Allotment	NY645105	04/09/08	04/09/08	Judith Allinson Sue Willis	No
CUSB	Sayle Bottom	NY655110	29/07/08 04/08/08	04/04/08	Janet Swain Sue Willis	Yes
CUSUN	Sunbiggin	NY646090	24/07/08 30/08/08	30/08/08	Robert Starling Sue Willis	Yes
HRCRAG	Hutton Roof Crags	SD557776	17/08/07 07/09/07	07/09/07	Sue Willis	No
HRDAL	Dalton Crags	SD552770	01/10/07	01/10/07	Judith Allinson Sue Willis	No
HRHPE	Holme Park Fell East	SD547790	21/08/07 23/08/07	21/08/07	Sue Willis	Yes
HRHPW	Holme Park West	SD540796	17/06/08	17/06/08	Mike Canaway Sue Willis	No
HRHQ	Holme Park Quarry	SD538788	22/07/08	22/07/08	Mike Canaway Sarah Learoyd Sue Willis	Yes
MBFAR	Farrar's Allotment	SD451860	02/06/08 27/06/08	02/06/08	Mike Canaway Sue Willis	Part
MBGB	Gait Barrows	SD479772	31/08/07	31/08/07	Sue Willis	No
MBHFA	High Farm Allotment	SD404791	16/07/08 28/07/08	28/07/08	Sue Willis Caroline Rosier	Yes
MBHW	Hampsfield Wood	SD402805	24/06/08 04/07/08	04/07/08	Mike Canaway Sue Willis	No
MBTQ	Trowbarrow Quarry	SD481761	13/05/08 23/05/08	13/05/08	Ian Henderson Sue Willis	Yes
MBUW	Underlaid Wood	SD485790	14/07/08	14/07/08	Sue Willis	Part
NWBA	Bryn Alyn	SJ198589	10/07/07 27/06/07 25/07/07	27/06/07	Sue Willis	Yes
NWBON	Boncs (aka Pentre Carreg Bach)	SH504839	14/06/08	No LIS	Sue Willis	No
NWBP	Bryn Pydew (aka Pen y Bont)	SH817798	12/07/07 15/08/07	15/08/07	Joanna Robertson Sue Willis	No
NWGO	Great Orme	SH757839	04/09/07 05/09/07	05/09/07	Sue Willis	No
NWMOE	Moelfre	SH514868	14/06/08	No LIS	Sue Willis	No
NWTAR	Taranau	SJ182720	27/08/08	27/08/08	Sue Willis	Part
IBCLAP	Clapdale Scars	SD749709	21/06/07 19/07/07	19/07/07	Hannah Fawcett Sue Willis	Yes
IBCOLT	Colt Park Wood	SD774778	24/05/07 23/04/08 09/05/08	09/05/08	Tim Thom Janet Swain Sue Willis	Yes
IBCRUM	Crummack Dale	SD772719	29/06/07 28/08/07 15/05/08	28/08/07	Hannah Fawcett Sue Willis	Yes

Study Code cont.	Pavement name	Grid ref	Date(s) of fieldwork	Date of LIS	Botanist(s) present	Prior species list?
IBSCAR	Scar Close	SD748771	30/08/07 25/09/08	25/09/08	Janet Swain Ann Gill Sue Willis	Yes
IBSUL	Sulber	SD774738	31/07/08 12/09/08	12/09/08	Hannah Fawcett Sue Willis	Yes
IBTC	Top Cow	SD782759	11/06/08	11/06/08	Janet Swain Sue Willis	Yes
KWPDH	Dale Head	SD840714	10/09/08	10/09/08	Janet Swain Sue Willis	No
KWPEWE	Ewe's Top	SD704758	27/09/07 29/09/07	29/09/07	Hannah Fawcett Sue Willis	Yes
KWPLS	Little Stainforth	SD810662	28/08/08 26/09/08	26/09/08	Janet Swain Sue Willis	Yes
KWPOLD	Old Ing	SD782774	02/08/07 05/08/07	02/08/07	Janet Swain Ann Gill Sue Willis	Yes
KWPOX	Oxenber Wood	SD781683	23/05/07 20/07/07 31/05/08	20/07/07	Ann Gill Sue Willis	Yes
KWPSC	Smearsett Copys	SD799683	06/08/08	06/08/08	Hannah Fawcett Sue Willis	Yes
MACBOR	Bordley	SD954648	17/07/07 24/07/07 19/03/08	24/07/07	Frances Graham Judith Allinson Sue Willis	Yes
MACBW	Bastow Wood	SD994654	07/05/08 14/05/08	14/05/08	Janet Swain Frances Graham Sue Willis	Yes
MACHCS	Hill Castles Scar	SD991684	20/08/08	20/08/08	Hannah Fawcett Sue Willis	Yes
MACLAN	Langcliffe	SD983721	06/08/07	06/08/07	Frances Graham Sue Willis	Yes
MACLG	Lea Green	SD997662	07/05/08 19/05/08 08/09/08	08/09/08	Janet Swain Sue Willis	Yes
MACMC	Malham Cove	SD897641	15/09/08 23/09/08	23/09/08	Sue Willis Caroline Rosier	Yes
MACTG	Tennant Gill	SD881694	29/05/08 04/06/08	29/05/08	Janet Swain Sue Willis	Yes
YORCAM	Cam High Road	SD854840	13/09/07	13/09/07	Janet Swain Sue Willis	Yes
YORGR	Greensett	SD747821	14/09/07	14/09/07	Hannah Fawcett Sue Willis	Yes
YORHAW	Hawkswick Clowder	SD947687	19/09/08	19/09/08	Hannah Fawcett Marie Peacock Sue Willis	Yes
YORRG	Rocky Ground	SD863735	28/07/07 02/08/07	02/08/07	Janet Swain Ann Gill Sue Willis	Yes
YORWF	Wold Fell	SD791850	10/09/07	10/09/07	Sue Willis Caroline Rosier	Yes

APPENDIX B: Species recorded, code names with English name

Abbrev. Name	Full Species Name	English Name
Acerpseu	*Acer pseudoplatanus*	Sycamore
Achimill	*Achillea millefolium*	Yarrow
Actaspic	*Actaea spicata*	Baneberry
Adoxmosc	*Adoxa moschatellina*	Town-hall clock
Aegopoda	*Aegopodium podagraria*	Ground elder
Aeschipp	*Aesculus hippocastanum*	Horse chestnut
Agrospp.	*Agrostis spp.*	Bent
Airacary	*Aira caryophyllea*	Silver hair-grass
Ajugrepe	*Ajuga repens*	Bugle
Alchspp.	*Alchemilla spp.*	Lady's mantle
Allipeti	*Alliaria petiolata*	Garlic mustard
Alliursi	*Allium ursinum*	Ramsons
Anemnemo	*Anemone nemorosa*	Wood anemone
Angesylv	*Angelica sylvestris*	Angelica
Antedioi	*Antennaria dioica*	Mountain everlasting
Anthodor	*Anthoxanthum odoratum*	Sweet vernal grass
Anthvuln	*Anthyllis vulneraria*	Kidney vetch
Arabhirs	*Arabis hirsuta*	Hairy rock cress
Armemari	*Armeria maritima*	Thrift
Arrhelat	*Arrhenatherum elatius*	False oat grass
Arummacu	*Arum maculatum*	Lords and ladies
Aspladia	*Asplenium adiantum-nigrum*	Black spleenwort
Asplruta	*Asplenium ruta-muraria*	Wall rue
Aspltric	*Asplenium trichomanes*	Maidenhair spleenwort
Asplviri	*Asplenium viride*	Green spleenwort
Athyfeli	*Athyrium felix-femina*	Lady fern
Atriundu	*Atrichum undulatum*	
Atriport	*Atriplex portulacoides*	Sea purslane
Bellpere	*Bellis perennis*	Daisy
Betupend	*Betula pendula*	Silver birch
Bracsylv	*Brachypodium sylvaticum*	False brome
Bracruta	*Brachythecium rutabulum*	
Brizmedi	*Briza media*	Quaking grass
Bromramo	*Bromopsis ramosa*	Hairy brome
Bryucapi	*Bryum capillare*	
Callcusp	*Calliergonella cuspidata*	
Callvulg	*Calluna vulgaris*	Heather
Calymuel	*Calypogeia muelleriana*	
Camplati	*Campanula latifolia*	Giant bellflower
Camprotu	*Campanula rotundifolia*	Harebell
Campintr	*Campylopus introflexus*	
Cardflex	*Cardamine flexuosa*	Wavy bitter-cress
Cardhirs	*Cardamine hirsuta*	Hairy bitter-cress
Cardimpa	*Cardamine impatiens*	Narrow-leaved bittercress
Cardprat	*Cardamine pratensis*	Cuckoo flower
Carecary	*Carex caryophyllea*	Spring sedge
Caredemi	*Carex demissa*	Common yellow sedge
Caredigi	*Carex digitata*	Fingered sedge
Careflac	*Carex flacca*	Glaucous sedge
Carenigr	*Carex nigra*	Common sedge
Carepani	*Carex panicea*	Carnation sedge
Carepuli	*Carex pulicaris*	Flea sedge
Carespp.	*Carex spp.*	
Caresylv	*Carex sylvatica*	Wood sedge
Carlvulg	*Carlina vulgaris*	Carline thistle
Centnigr	*Centaurea nigra*	Knapweed
Centscab	*Centaurea scabiosa*	Greater knapweed
Centrube	*Centranthus ruber*	Red valerian
Ceradiff	*Cerastium diffusum*	Sea mouse-ear
Cerafont	*Cerastium fontanum*	Common mouse-ear
Ceteoffi	*Ceterach officinarum*	Rusty-back fern
Chamangu	*Chamerion angustifolium*	Rosebay willowherb
Chryoppo	*Chrysosplenium oppositifolium*	Opp leaved golden saxifrage
Circlute	*Circaea lutetiana*	Enchanter's nightshade
Cirrpili	*Cirriphyllum piliferum*	
Cirsarve	*Cirsium arvense*	Creeping thistle
Cirshete	*Cirsium heterophyllum*	Melancholy thistle
Cirspalu	*Cirsium palustre*	Marsh thistle
Cirsspp.	*Cirsium spp.*	Thistle
Cirsvulg	*Cirsium vulgare*	Spear thistle
Clemvita	*Clematis vitalba*	Clematis
Climdend	*Climacium dendroides*	
Clinvulg	*Clinopodium vulgare*	Wild basil
Cochoffi	*Cochlearia officinalis*	Scurvy-grass
Conospp.	*Conocephalum spp.*	
Conomaju	*Conopodium majus*	Pignut
Convmaja	*Convallaria majalis*	Lily-of-the-valley
Cornsang	*Cornus sanguinea*	Dogwood
Coryavel	*Corylus avellana*	Hazel
Cotohori	*Cotoneaster horizontalis*	
Cotospp.	*Cotoneaster spp.*	Cotoneaster
Cratmono	*Crataegus monogyna*	Hawthorn
Creppalu	*Crepis paludosa*	Marsh hawk's-beard
Cruclaev	*Cruciata laevipes*	Crosswort
Ctenmoll	*Ctenidium molluscum*	
Cynocris	*Cynosurus cristatus*	Crested dog's-tail
Cystfrag	*Cystopteris fragilis*	Brittle bladder-fern
Dactglom	*Dactylis glomerata*	Cocksfoot
Dantdecu	*Danthonia decumbens*	Heath grass
Desccesp	*Deschampsia cespitosa*	
Dicrhete	*Dicranella heteromalla*	
Dicrscop	*Dicranum scoparium*	
Digipurp	*Digitalis purpurea*	Foxglove
Ditrgrac	*Ditrichum gracile*	
Dryaocto	*Dryas octopetala*	Mountain avens
Dryocart	*Dryopteris carthusiana*	Narrow buckler fern
Dryodili	*Dryopteris dilitata*	Broad buckler fern
Dryofili	*Dryopteris filix-mas*	Common male fern
Dryosubm	*Dryopteris submontana*	Rigid buckler fern
Empenigr	*Empetrum nigrum*	Crowberry
Encastre	*Encalypta streptocarpa*	
Epilbrun	*Epilobium brunnescens*	New Zealand willow-herb
Epilmont	*Epilobium montanum*	Broad leaved willow-herb
Epipatro	*Epipactis atrorubens*	Dark-red helleborine
Epiphell	*Epipactis helleborine*	Broad-leaved helleborine
Ericcine	*Erica cinerea*	Bell heather
Eropvern	*Erophila verna*	Whitlow grass
Euoneuro	*Euonymus europaeus*	Spindle
Eupacann	*Eupatorium cannabinum*	Hemp-agrimony
Euphnemo	*Euphrasia nemorosa*	Eyebright
Eurhprae	*Eurhynchium praelongum*	
Eurhstri	*Eurhynchium striatum*	
Fagusylv	*Fagus sylvatica*	Beech
Festovin	*Festuca ovina*	Sheep's fescue
Festrubr	*Festuca rubra*	Red fescue
Festspp.	*Festuca spp.*	
Filiulma	*Filipendula ulmaria*	Meadowsweet
Filivulg	*Filipendula vulgaris*	Dropwort
Fissspp.	*Fissidens spp.*	
Fragvesc	*Fragaria vesca*	Wild strawberry
Fraxexce	*Fraxinus excelsior*	Ash
Galaniva	*Galanthus nivalis*	Snowdrop
Galiapar	*Galium aparine*	Cleavers
Galiodor	*Galium odoratum*	Woodruff
Galister	*Galium sterneri*	Limestone bedstraw
Galiveru	*Galium verum*	Lady's bedstraw
Geraluci	*Geranium lucidum*	Shining crane's-bill
Geraprat	*Geranium pratense*	Meadow crane's-bill
Gerarobe	*Geranium robertianum*	Herb robert
Gerasang	*Geranium sanguinium*	Bloody crane's-bill
Gerasylv	*Geranium sylvaticum*	Wood crane's-bill
Geumriva	*Geum rivale*	Water avens
Geumurba	*Geum urbanum*	Wood avens
Glechede	*Glechoma hederacea*	Ground-ivy
Grimspp.	*Grimmia spp.*	
Gymnrobe	*Gymnocarpium robertianum*	Limestone fern
Hedeheli	*Hedera helix*	Ivy
Helinumm	*Helianthemum nummularium*	Common rock-rose
Helioela	*Helianthemum oelandicum*	Hoary rock-rose
Heliprat	*Helictotrichon pratense*	Meadow oat grass
Helipube	*Helictotrichon pubescens*	Downy oat grass
Heraspho	*Heracleum sphondylium*	Hogweed
Hierspp.	*Hieracium spp.*	Hawkweed
Holclana	*Holcus lanatus*	Yorkshire fog
Homaspp.	*Homalothecium spp.*	
Hyacnon-	*Hyacinthoides non-scripta*	Bluebell

Abbrev. Name	Full Species Name	English Name
Hylosple	*Hylocomium splendens*	
Hypeandr	*Hypericum androsaemum*	Tutsan
Hypemont	*Hypericum montanum*	Pale St John's wort
Hypespp.	*Hypericum spp.*	
Hypncupr	*Hypnum cupressiforme agg*	
Hypnjutl	*Hypnum jutlandicum*	
Hyporadi	*Hypochaeris radicata*	Cat's-ear
Ilexaqui	*Ilex aquifolium*	Holly
Inulcony	*Inula conyzae*	Ploughman's-spikenard
Juglregi	*Juglans regia*	Walnut
Juncarti	*Juncus articulatus*	Jointed rush
Junceffu	*Juncus effuses*	
Jungspp.	*Jungermannia spp.*	
Junicomm	*Juniperus communis*	Juniper
Koelmacr	*Koeleria macrantha*	Crested hair-grass
Larideci	*Larix decidua*	Larch
Lathprat	*Lathyrus pratensis*	Yellow meadow vetchling
Leonhisp	*Leontodon hispidus*	Hairy hawkbit
Liguvulg	*Ligustrum vulgare*	Wild privet
Linucart	*Linum carthartіcum*	Fairy flax
Listovat	*Listera ovata*	Twayblade
Lolipere	*Lolium perenne*	Perennial rye grass
Loniperi	*Lonicera periclymenum*	Honeysuckle
Lophbide	*Lophocolea bidentata*	
Lotucorn	*Lotus corniculatus*	Bird's-foot trefoil
Luzucamp	*Luzula campestris*	Field woodrush
Luzusylv	*Luzula sylvatica*	Greater woodrush
Mecocamb	*Meconopsis cambrica*	Welsh poppy
Melinuta	*Melica nutans*	Mountain melick
Meliunif	*Melica uniflora*	Wood melick
Mercpere	*Mercurialis perennis*	Dog's mercury
Mniuhorn	*Mnium hornum*	
Molicaer	*Molinia caerulea*	Purple moor-grass
Mycemura	*Mycelis muralis*	Wall lettuce
Myosspp.	*Myositis spp.*	Forget-me-not
Nardstri	*Nardus stricta*	Mat-grass
Neckcomp	*Neckera complanata*	
Neckcris	*Neckera crispa*	
Orchmasc	*Orchis mascula*	Early purple orchid
Orchspp.	*Orchis spp.*	
Oxalacet	*Oxalis acetosella*	Wood-sorrel
Pariquad	*Paris quadrifolia*	Herb paris
Pellepip	*Pellia epiphylla*	
Phalarun	*Phalaris arundinacea*	Reed canary-grass
Phylscol	*Phyllitis scolopendrium*	Hart's-tongue
Pilooffi	*Pilosella officinarum*	Mouse-ear hawkweed
Pimpsaxi	*Pimpinella saxifraga*	Burnet-saxifrage
Pinusylv	*Pinus sylvestris*	Scots pine
Plagspp.	*Plagiomnium spp.*	
Planlanc	*Plantago lanceolata*	Ribwort plantain
Planmajo	*Plantago major*	Greater plantain
Planmari	*Plantago maritima*	Sea plantain
Planmedi	*Plantago media*	
Poa spp.	*Poa spp.*	
Polyserp	*Polygala serpyllifolia*	
Polyspp.	*Polygala spp.*	Milkwort
Polyodor	*Polygonatum odoratum*	Angular Solomon's seal
Polyaust	*Polypodium australe*	
Polyinte	*Polypodium interjectum*	
Polyvulg	*Polypodium vulgare*	Common polypody
Polyacul	*Polystichum aculeatum*	Hard shield-fern
Polylonc	*Polystichum lonchitis*	Holly fern
Polymoss	*Polytrichum moss*	
Porespp.	*Porella spp.*	
Potecran	*Potentilla crantzii*	Alpine cinquefoil
Poteerec	*Potentilla erecta*	Tormentil
Potester	*Potentilla sterilis*	Barren strawberry
Primfari	*Primula farinosa*	Bird's-eye primrose
Primveri	*Primula veris*	Cowslip
Primvulg	*Primula vulgaris*	Primrose
Prunvulg	*Prunella vulgaris*	Selfheal
Prunaviu	*Prunus avium*	Wild cherry
Prunpadu	*Prunus padus*	Bird cherry
Prunspin	*Prunus spinosa*	Blackthorn

Abbrev. Name	Full Species Name	English Name
Pseupure	*Pseudoscleropodium purens*	
Pteraqui	*Pteridium aquilinum*	Bracken
Querpetr	*Quercus petraea*	Sessile oak
Querspp.	*Quercus spp*	Oak
Racolanu	*Racomitrium lanuginosum*	
Ranuacri	*Ranunculus acris*	Meadow buttercup
Ranubulb	*Ranunculus bulbosus*	Bulbous buttercup
Ranufica	*Ranunculus ficaria*	Lesser celandine
Ranurepe	*Ranunculus repens*	Creeping buttercup
Rhamcath	*Rhamnus cathartica*	Common buckthorn
Rhynconf	*Rhynchostegium confertum*	
Rhytsqua	*Rhytidiadelphus squarrosus*	
Rhyttriq	*Rhytidiadelphus triquetrus*	
Ribespic	*Ribes spicatum*	Downy currant
Ribeuva-	*Ribes uva-crispa*	Gooseberry
Rosacani	*Rosa canina*	Dog-rose
Rosapimp	*Rosa pimpinellifolia*	Burnet rose
Rubipere	*Rubia peregrina*	Wild madder
Rubufrut	*Rubus fruticosus*	Bramble
Rubuidae	*Rubus idaeus*	Raspberry
Rubusaxa	*Rubus saxatilis*	Stone bramble
Rumeacet	*Rumex acetosa*	Sorrel
Rumeobtu	*Rumex obtusifolius*	Broad leaved dock
Saginodo	*Sagina nodosa*	Knotted pearlwort
Salicapr	*Salix caprea*	Goat willow
Salicine	*Salix cinerea*	Grey willow
Salispp.	*Salix spp.*	
Sambnigr	*Sambucus nigra*	Elder
Sangmino	*Sanguisorba minor*	Salad burnet
Sangoffi	*Sanguisorba officinalis*	Greater burnet
Sanieuro	*Sanicula europaea*	Sanicle
Saxihypn	*Saxifraga hypnoides*	Mossy saxifrage
Saxitrid	*Saxifraga tridactylites*	Rue-leaved saxifrage
Scabcolu	*Scabiosa columbaria*	Small scabious
Scapspp.	*Scapania spp.*	
Schiapoc	*Schistidium apocarpum*	
Scronodo	*Scrophularia nodosa*	Common figwort
Seduacre	*Sedum acre*	Biting stonecrop
Seduangl	*Sedum anglican*	English stonecrop
Seduspp.	*Sedum spp.*	
Sedutele	*Sedum telephium*	Orpine
Selasela	*Selaginella selaginoides*	Lesser clubmoss
Senejaco	*Senecio jacobaea*	Ragwort
Seslcaer	*Sesleria caerulea*	Blue moor grass
Sherarve	*Sherardia arvensis*	Field madder
Siledioi	*Silene dioica*	Red campion
Soladulc	*Solanum dulcamara*	Woody nightshade
Solivirg	*Solidago virgaurea*	Goldenrod
Soncspp.	*Sonchus spp.*	Sow-thistle
Sorbaria	*Sorbus aria*	Common whitebeam
Sorbaucu	*Sorbus aucuparia*	Rowan
Stacsylv	*Stachys sylvatica*	Hedge woundwort
Stelholo	*Stellaria holostea*	Greater stitchwort
Stelmedi	*Stellaria media*	Chickweed
Succprat	*Succisa pratensis*	Devil's-bit scabious
Tamucomm	*Tamus communis*	Black bryony
Taraoffi	*Taraxacum officinalis*	Dandelion
Taxubacc	*Taxus baccata*	Yew
Teucscor	*Teucrium scorodonia*	Wood sage
Thalminu	*Thalictrum minus*	Lesser meadow-rue
Thamspp.	*Thamnobryum spp.*	
Thuitama	*Thuidium tamariscinum*	
Thujplic	*Thuja plicata*	Western red cedar
Thympoly	*Thymus polytrichus*	Wild thyme
Torttort	*Tortella tortuosa*	
Trifspp.	*Trifolium spp.*	Clover
Trisflav	*Trisetum flavescens*	Yellow oat grass
Troleuro	*Trollius europaeus*	Globeflower
Tussfarf	*Tussilago farfara*	Colt's-foot
Ulexeuro	*Ulex europaeus+A162*	Gorse
Ulmuglab	*Ulmus glabra*	Wych elm
Urtidioi	*Urtica dioica*	Nettle
Vaccmyrt	*Vaccinium myrtillus*	Bilberry
Valeoffi	*Valeriana officinalis*	Common valerian

Abbrev. Name	Full Species Name	English Name
Verbthap	*Verbascum thapsus*	Great mullein
Verocham	*Veronica chamaedrys*	Germander speedwell
Veromont	*Veronica montana*	Wood speedwell
Verooffi	*Veronica officinalis*	Heath speedwell
Veroserp	*Veronica serpyllifolia*	Thyme-leaved speedwell
Verospic	*Veronica spicata*	Spiked speedwell
Vibuopul	*Viburnum opulus*	Guelder-rose

Abbrev. Name	Full Species Name	English Name
Vicicrac	*Vicia cracca*	Tufted vetch
Vicisepi	*Vicia sepium*	Bush vetch
Violhirt	*Viola hirta*	Hairy violet
Viollute	*Viola lutea*	Pansy
Violrivi	*Viola riviniana*	Common dog violet
Weisspp.	*Weissia spp.*	

APPENDIX C: Species recorded on the 46 limestone pavements (presence marked x)

Species code	CUCLO	CUGAS	CURA	CUSB	CUSUN	HRCRAG	HRDAL	HRHPE	HRHPW	HRHQ	IBCLAP	IBCOLT	IBCRUM	IBSCAR	IBSUL	IBTC	KWPDH	KWPEWE	KWPLS	KWPOLD	KWPOX	KWPSC	MACBOR	MACBW	MACHCS	MACLAN	MACLG	MACMC	MACTG	MBFAR	MBGB	MBHFA	MBHW	MBTQ	MBUW	NWBA	NWBON	NWBP	NWGO	NWMOE	NWTAR	YORCAM	YORGR	YORHAW	YORRG	YORWF
Acerpseu		X	X	X		X	X	X	X	X		X	X	X		X	X		X		X			X	X		X				X	X	X	X	X	X	X	X			X					
Achimill														X								X					X		X													X	X		X	
Actaspic												X		X														X																		
Adoxmosc												X																																		
Aegopoda																X								X																						
Aeschipp												X																																		
Agrospp.					X					X		X												X			X														X	X	X			X
Airacary																																					X									
Ajugrepe				X																																										
Alchspp.																					X																						X			
Allipeti												X																																		
Alliursi		X		X	X				X			X		X	X	X				X	X	X					X		X					X		X										
Anemnemo	X		X	X	X			X	X	X		X		X	X	X	X				X	X		X	X		X		X			X				X								X		
Angesylv	X								X					X																																
Antedioi																					X																									
Anthodor									X					X		X	X			X								X	X			X	X				X									
Anthvuln																																						X								
Arabhirs	X		X	X	X		X							X		X					X				X				X				X													
Armemari																																								X						
Arrhelat							X									X	X			X								X	X				X			X										
Arummacu									X		X	X				X		X			X			X			X							X			X									
Aspladia												X																											X							
Asplruta	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X
Aspltric	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Asplviri	X	X	X	X	X	X	X				X		X	X	X	X	X	X	X	X	X	X	X		X	X			X													X	X	X	X	X
Athyfeli	X	X	X		X		X						X	X	X			X				X			X							X							X					X		
Atriundu							X					X																					X													
Atriport																																								X						
Bellpere																																										X	X			
Betupend																								X						X	X				X											
Bracsylv		X			X	X	X	X	X	X			X	X					X		X	X		X	X					X	X	X	X	X	X		X	X	X		X			X		
Bracruta		X										X				X					X	X				X	X						X	X							X					X
Brizmedi			X	X					X				X		X	X	X		X		X	X			X							X	X				X		X		X	X				
Bromramo																																	X													
Bryucapi							X				X															X																				
Callcusp		X																						X				X																		
Callvulg			X											X																																
Camplati												X																																		
Camprotu			X		X					X			X	X		X	X		X	X			X						X			X						X			X	X	X	X		
Campintr							X																							X																
Cardflex												X				X													X																X	
Cardhirs							X							X						X			X	X			X	X	X														X	X		

Spp. code (cont.)	CUCLO	CUGAS	CURA	CUSB	CUSUN	HRCRAG	HRDAL	HRHPE	HRHPW	HRHQ	IBCLAP	IBCOLT	IBCRUM	IBSCAR	IBSUL	IBTC	KWPDH	KWPEWE	KWPLS	KWPOLD	KWPOX	KWPSC	MACBOR	MACBW	MACHCS	MACLAN	MACLG	MACMC	MACTG	MBFAR	MBGB	MBHFA	MBHW	MBTQ	MBUW	NWBA	NWBON	NWBP	NWGO	NWMOE	NWTAR	YORCAM	YORGR	YORHAW	YORRG	YORWF
Cardimpa												X								X																X										
Cardprat												X		X		X	X												X													X	X	X	X	
Carecary			X																				X																							
Caredemi																X		X													X															
Careflac		X	X				X		X	X						X	X	X	X		X				X				X	X		X	X			X		X			X			X		
Carenigr									X							X													X	X				X				X								
Carepani			X											X		X	X		X																X		X						X			
Carepuli			X		X	X		X		X			X			X		X							X												X									
Carespp.																										X								X												
Caresylv															X						X										X															
Carlvulg									X	X											X	X										X				X										
Centnigr								X	X	X				X		X												X		X	X							X								
Centscab														X																																
Centrube																																						X								
Ceradiff																																								X						
Cerafont			X									X		X				X					X				X		X												X		X	X		
Chamangu	X		X	X	X	X	X	X		X			X	X			X					X			X				X	X													X	X		
Chryoppo												X					X																										X			
Circlute												X									X									X				X				X								
Cirsarve		X	X	X	X				X		X			X	X	X	X	X	X	X		X			X	X		X	X			X							X					X	X	
Cirshete														X		X										X																				
Cirspalu				X										X		X	X	X					X			X																	X		X	X
Cirsspp.								X																													X									
Cirsvulg	X	X	X	X	X						X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X				X					X	X	X	X	X	
Clemvita																																					X	X								
Climdend										X		X						X		X		X																				X	X		X	X
Clinvulg	X																																													
Cochoffi																	X																							X						
Conospp.	X	X	X	X	X					X	X			X	X		X	X					X					X	X	X												X	X	X		
Conomaju												X																																		
Convmaja							X	X				X		X					X											X																
Cornsang									X																																					
Coryavel		X	X	X		X	X	X	X	X		X		X	X	X			X		X			X	X					X		X		X	X		X									
Cotohori										X																																				
Cotospp.							X	X																								X						X	X							
Cratmono	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X		X	X		X	X			X	X	X	X	X	X	X	X	X		X			X	X	
Creppalu												X													X																					
Cruclaev																	X											X																		
Ctenmoll	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	X		X	X	X	X
Cynocris																X																														
Cystfrag	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X							X			X			X	X	X		X
Dactglom						X			X	X						X	X											X					X	X			X									
Dantdecu			X				X		X		X																																			

Spp. code (cont.)	CUCLO	CUGAS	CURA	CUSB	CUSUN	HRCRAG	HRDAL	HRHPE	HRHPW	HRHQ	IBCLAP	IBCOLT	IBCRUM	IBSCAR	IBSUL	IBTC	KWPDH	KWPEWE	KWPLS	KWPOLD	KWPOX	KWPSC	MACBOR	MACBW	MACHCS	MACLAN	MACLG	MACMC	MACTG	MBFAR	MBGB	MBHFA	MBHW	MBTQ	MBUW	NWBA	NWBON	NWBP	NWGO	NWMOE	NWTAR	YORCAM	YORGR	YORHAW	YORRG	YORWF
Desccesp						X														X					X		X															X				
Dicrscop		X		X			X				X										X			X									X			X							X			
Digipurp										X																																				
Ditrgrac	X		X		X		X							X		X	X	X			X	X	X					X	X														X	X		
Dryodili												X		X		X	X			X	X			X									X													
Dryofili	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X		X		X	X		
Dryosubm	X	X	X	X		X	X	X	X	X			X					X											X	X		X	X												X	
Empenigr														X																																
Encastre		X	X				X															X					X		X																	
Epilbrun			X																																											
Epilmont	X		X	X	X		X		X		X	X		X	X	X	X	X				X	X		X			X	X			X	X		X								X	X	X	
Epipatro										X																				X																
Epiphell						X		X																																						
Ericcine			X																																		X	X								
Eropvern																	X											X	X																	
Euoneuro																																					X									
Eupacann								X																														X								
Euphnemo	X				X					X	X						X									X						X						X					X	X	X	X
Eurhprae												X			X									X																		X				
Eurhstri										X							X											X																		
Fagusylv																																	X		X											
Festovin			X	X	X	X	X	X	X		X		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X						X	X	X				X	X	X	X	X
Festrubr	X	X							X	X			X		X	X	X		X				X		X	X		X	X	X			X		X	X				X	X	X	X			
Festspp.																															X															
Filiulma									X			X		X		X	X			X	X			X					X					X								X			X	
Filivulg									X	X																					X								X							
Fissspp.			X				X		X	X				X	X	X	X		X									X		X					X	X					X			X		
Fragvesc							X	X		X	X	X		X		X	X				X			X		X	X		X		X		X		X	X	X	X			X	X				
Fraxexce	X		X		X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X			X			X		
Galaniva												X																																		
Galiapar				X					X		X	X				X				X														X												
Galiodor									X			X												X																						
Galister		X	X	X	X						X	X		X		X	X		X		X	X			X		X	X	X			X	X									X	X	X		
Galiveru			X											X					X																			X			X					
Geraluci												X		X		X	X											X	X																	
Geraprat																													X																	
Gerarobe	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Gerasang														X	X						X			X	X						X						X	X								
Gerasylv												X																	X																	
Geumriva												X		X							X								X																	
Geumurba												X		X		X				X				X									X	X												
Glechede																											X	X																	X	
Grimspp.			X	X					X													X					X	X								X		X	X		X					

Spp. code (cont.)	CUCLO	CUGAS	CURA	CUSB	CUSUN	HRCRAG	HRDAL	HRHPE	HRHPW	HRHQ	IBCLAP	IBCOLT	IBCRUM	IBSCAR	IBSUL	IBTC	KWPDH	KWPEWE	KWPLS	KWPOLD	KWPOX	KWPSC	MACBOR	MACBW	MACHCS	MACLAN	MACLG	MACMC	MACTG	MBFAR	MBGB	MBHFA	MBHW	MBTQ	MBUW	NWBA	NWBON	NWBP	NWGO	NWMOE	NWTAR	YORCAM	YORGR	YORHAW	YORRG	YORWF
Gymnrobe		X	X			X		X	X						X		X					X	X		X					X						X								X	X	
Hedeheli		X	X	X	X	X	X	X	X	X				X	X	X		X	X		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X		X			X		
Helinumm														X					X		X			X	X		X		X	X					X		X	X			X					
Heliprat			X						X							X																														
Helipube																												X		X	X															
Heraspho							X					X	X	X		X	X	X		X			X		X			X	X							X								X	X	
Hierspp.			X	X					X	X				X	X	X		X	X	X	X		X		X			X		X		X			X	X		X					X			
Holclana				X								X				X								X				X					X													
Homaspp.	X		X	X		X	X				X		X	X		X	X		X	X	X	X	X		X		X	X	X		X	X			X	X		X	X	X	X	X	X	X	X	X
Hyacnon-									X			X		X	X									X			X		X					X												
Hylosple							X							X																																
Hypeandr																																					X									
Hypemont								X																														X								
Hypespp.														X	X														X	X							X									
Hypncupr		X	X				X		X					X						X	X		X			X	X			X	X			X				X					X			
Hyporadi														X						X																										
Ilexaqui						X	X	X	X	X									X		X	X		X	X						X	X	X	X	X	X		X			X					
Inulcony								X	X	X																									X				X							
Juglregi							X																																							
Juncarti																		X																						X						
Junceffu																																											X			
Jungspp.		X																																												
Junicomm						X		X		X																				X		X	X		X			X								
Koelmacr																					X																									
Larideci					X																			X										X												
Leonhisp	X							X	X	X												X			X					X		X				X					X					
Liguvulg																								X						X							X	X	X							
Linucart	X		X	X		X				X							X		X							X										X		X						X		X
Listovat									X	X	X																			X																
Lolipere																												X																		
Loniperi		X	X						X												X			X	X					X			X		X		X	X								
Lophbide																								X																						
Lotucorn										X				X		X			X	X							X					X		X	X	X		X	X				X			
Luzucamp																							X						X													X	X			X
Luzusylv														X																																
Mecocamb					X																																									
Melinuta		X	X			X		X		X				X				X											X	X	X				X									X	X	
Meliunif							X		X	X																								X												
Mercpere	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		X	X	X	X	X	X	X	X	X			X	X	X		X	X	X	X		X		X	X	X	X
Mniuhorn		X		X						X		X									X	X		X									X							X				X		
Molicaer			X											X			X	X													X															
Mycemura	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X			X	X	X		X	X		X	X	X	X			X			X	X	
Myosspp.																X	X						X	X		X	X		X																X	

Spp. code (cont.)	CUCLO	CUGAS	CURA	CUSB	CUSUN	HRCRAG	HRDAL	HRHPE	HRHPW	HRHQ	IBCLAP	IBCOLT	IBCRUM	IBSCAR	IBSUL	IBTC	KWPDH	KWPEWE	KWPLS	KWPOLD	KWPOX	KWPSC	MACBOR	MACBW	MACHCS	MACLAN	MACLG	MACMC	MACTG	MBFAR	MBGB	MBHFA	MBHW	MBTQ	MBUW	NWBA	NWBON	NWBP	NWGO	NWMOE	NWTAR	YORCAM	YORGR	YORHAW	YORRG	YORWF
Nardstri																											X										X						X			
Neckcomp																																	X	X												
Neckcris	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	
Orchmasc																					X						X		X	X			X	X												
Orchspp.													X			X																					X									
Oxalacet	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X	X	X			X	X			X					X	X	X	X	X	X
Pariquad												X												X					X																	
Phalarun																	X																													
Phylscol	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X			X	X	
Pilooffi								X	X	X				X																		X		X		X		X	X							
Pimpsaxi										X						X																					X	X	X							
Pinusylv																														X																
Plagspp.		X	X		X		X			X					X		X					X			X		X	X	X															X		
Planlanc														X																		X		X				X	X		X					
Planmari																																								X						
Planmedi																																										X				
Poa spp.							X																					X								X						X				
Polyserp																														X																
Polyspp.																					X																									
Polyodor								X	X	X																					X													X		
Polyaust																															X							X								
Polyinte																														X																
Polyvulg						X	X					X		X	X	X	X			X		X	X				X						X	X			X				X					
Polyacul	X	X	X	X	X	X		X	X	X		X	X	X	X	X	X	X				X			X			X	X	X		X	X		X	X								X		
Polylonc			X																																											
Polymoss							X					X		X	X						X												X		X							X	X			
Porespp.												X																																		
Potecran																					X																									
Poteerec			X																											X		X														
Potester																X	X		X		X												X	X				X					X			
Primfari																													X																	
Primveri								X													X						X							X												
Primvulg									X			X	X	X		X	X			X				X					X				X	X									X		X	
Prunvulg																	X		X			X	X	X		X	X																X			
Prunaviu												X																																		
Prunpadu												X				X																														
Prunspin						X		X	X	X				X		X				X				X	X					X	X	X	X	X	X		X	X	X							
Pseupure	X	X					X										X						X	X			X		X			X	X		X	X						X				
Pteraqui		X		X		X	X	X	X	X		X	X	X		X					X			X	X					X			X	X	X	X	X	X			X					
Querpetr										X																							X								X					
Querspp.																															X			X	X			X								
Racolanu	X													X																												X				
Ranuacri																X												X																		

Spp. code (cont.)	CUCLO	CUGAS	CURA	CUSB	CUSUN	HRCRAG	HRDAL	HRHPE	HRHPW	HRHQ	IBCLAP	IBCOLT	IBCRUM	IBSCAR	IBSUL	IBTC	KWPDH	KWPEWE	KWPLS	KWPOLD	KWPOX	KWPSC	MACBOR	MACBW	MACHCS	MACLAN	MACLG	MACMC	MACTG	MBFAR	MBGB	MBHFA	MBHW	MBTQ	MBUW	NWBA	NWBON	NWBP	NWGO	NWMOE	NWTAR	YORCAM	YORGR	YORHAW	YORRG	YORWF
Ranufica												X				X							X																							
Ranurepe																													X														X			
Rhamcath							X					X							X		X											X	X	X	X											
Rhytsqua												X		X			X			X						X	X													X		X		X	X	X
Rhyttriq		X	X		X										X						X	X			X		X	X	X							X				X				X		X
Ribespic														X		X													X																	
Ribeuva-																X																		X												
Rosacani		X	X				X	X	X	X				X							X	X		X	X					X	X		X	X	X	X	X	X			X					
Rosapimp																																					X									
Rubipere																																						X								
Rubufrut						X	X	X	X	X				X		X					X			X						X	X	X	X	X	X		X	X	X		X					
Rubuidae	X											X		X	X		X				X			X	X							X					X									
Rubusaxa			X	X										X		X																														
Rumeacet																X				X									X																	
Rumeobtu												X																																		
Salicapr														X																				X												
Salicine										X														X																				X		
Salispp.	X		X															X											X																	
Sambnigr		X						X	X	X	X	X		X	X	X	X		X	X		X	X		X		X	X				X				X								X	X	
Sangmino																				X											X					X		X			X					
Sangoffi															X																															
Sanieuro	X		X						X	X			X		X			X	X	X	X	X	X		X				X										X					X		
Saxihypn												X					X				X											X										X	X			X
Saxitrid			X		X					X	X																																			
Scabcolu									X					X		X				X	X											X				X							X			
Scapspp.	X		X		X		X									X	X				X								X	X			X												X	
Schiapoc			X				X														X																								X	
Scronodo											X				X	X	X											X																		
Seduacre				X			X	X	X	X				X			X			X						X	X	X								X										
Seduspp.																																					X									
Sedutele																															X															
Selasela			X																																											
Senejaco		X	X				X	X	X	X	X			X		X	X	X	X			X		X	X		X	X	X	X		X		X		X	X	X			X			X		
Seslcaer	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X			X	X	X	X	X
Sherarve									X																																					
Siledioi												X				X	X			X									X																X	
Soladulc										X																				X																
Solivirg									X	X																					X							X								
Soncspp.						X		X	X																	X		X								X			X		X					
Sorbaria										X																				X								X			X					
Sorbaucu						X			X	X	X	X	X	X	X	X	X		X		X	X		X							X		X	X							X					
Stacsylv	X													X	X	X	X			X			X					X	X															X	X	
Stelholo												X								X																										

Spp. code (cont.)	CUCLO	CUGAS	CURA	CUSB	CUSUN	HRCRAG	HRDAL	HRHPE	HRHPW	HRHQ	IBCLAP	IBCOLT	IBCRUM	IBSCAR	IBSUL	IBTC	KWPDH	KWPEWE	KWPLS	KWPOLD	KWPOX	KWPSC	MACBOR	MACBW	MACHCS	MACLAN	MACLG	MACMC	MACTG	MBFAR	MBGB	MBHFA	MBHW	MBTQ	MBUW	NWBA	NWBON	NWBP	NWGO	NWMOE	NWTAR	YORCAM	YORGR	YORHAW	YORRG	YORWF
Stelmedi												X																																		
Succprat						X						X	X	X										X														X								
Tamucomm																																X	X	X			X									
Taraoffi	X		X	X	X		X	X	X	X		X		X	X	X	X	X	X			X		X		X	X	X	X	X		X	X			X	X	X	X		X	X	X	X		X
Taxubacc							X	X	X	X	X																			X	X	X	X	X	X			X	X							
Teucscor			X				X	X	X	X				X		X				X	X			X	X					X	X	X	X	X	X		X	X	X							X
Thalminu				X		X			X		X		X	X	X	X		X			X	X			X	X				X						X		X	X					X	X	
Thamspp.			X				X					X			X	X	X				X		X	X	X		X	X	X				X	X										X	X	
Thuitama		X		X			X					X		X			X					X		X					X				X	X												
Thujplic																														X					X											
Thympoly	X		X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X			X	X	X	X	X			X	X		X	X			X		X	X	X	X	X	X
Torttort	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X
Trifspp.																							X			X			X												X	X	X			
Trisflav																													X																	
Troleuro												X		X															X																	
Tussfarf									X	X								X	X										X																	
Ulexeuro								X	X	X																										X	X		X		X					
Ulmuglab										X																X						X	X	X	X	X					X					
Urtidioi	X	X	X	X	X				X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X				X			X			X		X	X	X	X	X	
Vaccmyrt					X									X																																
Valeoffi														X	X	X									X			X	X			X						X							X	
Verbthap																														X																
Verocham												X				X				X				X					X								X					X				
Veromont			X																														X													
Verooffi														X									X																							
Veroserp																								X																						
Vibuopul							X	X		X				X																X																
Vicisepi												X		X		X	X			X									X																	
Violhirt					X				X	X				X							X			X						X		X			X		X									
Viollute																											X		X																	
Violrivi	X	X	X	X	X		X	X		X			X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X		X	X			X	X		X		X	X	X	X	X	
Weisspp.							X																																							

APPENDIX D: Habitat Definition (Ward, 2007)

Limestone Pavement: definition

Legislative basis
Limestone pavement was first recognised as being of national importance in the UK under the *Wildlife & Countryside Act 1981* and subsequently as of European importance under the *Habitats and Species Directive 1992*, under which it is listed in Annex 1 as a priority habitat.

Under the 1981 Act, limestone pavement means *"an area of limestone which lies wholly or partly exposed on the surface of the ground & has been fissured by natural erosion".* For clarity, Natural England adds that it *'usually demonstrates a pattern of clints and grikes'.*

Geodiversity
Thought of in the abstract, limestone pavement - with its clints and grikes - should be easy to define.[1] But this is not the case in practice: the dilemma is evident in the phrase *'wholly or partly exposed'* contained in the legal definition. Pavements can vary, sometimes within the one site, from:

- massive blocks of relatively unweathered limestone usually, but not always, with well developed grikes;
- areas where the clint and grike structure, although evident, is masked by vegetation;
- finely fractured areas, where the limestone may be reduced to little more than shillet, i.e. fragments left after the clints lose all coherence. A form of shillett may remain following mechanical removal of larger clints.

Biodiversity
Given the structural range of pavements, there is a correspondingly wide range of associated vegetation types, dependent not just on the pavement type, but influenced by land management. In combination, pavement structure and management support:

- woodland where, under a canopy of ash which admits light for much of the year, the clints are clothed in rampant woodland flora and the grikes concealed underfoot. Such is the case at Colt Park Wood, part of Ingleborough NNR, where the danger posed to livestock may account for the wood's survival;
- woodland where, under a canopy of hazel or yew which admit little light, a pattern of clints can be discerned, but usually covered in bryophytes and with the grikes typically choked with leaf litter. (Similar circumstances may pertain where commercial coniferous trees have been planted on pavement; in such circumstances, the grikes may be choked with a 'needle' leaf litter.)
- exposures of limestone so massive and bare as to form natural woodland clearings or large expanses within upland pastures. It is the deeper grikes in these pavements which provide niches for a distinctive pavement flora, i.e. one with species reliant upon either the humid and shaded microclimate or protection from grazing provided by the grikes.
- where the clints are *'wholly or partly exposed'* – it is in these circumstances where mosaics of limestone pavement with other vegetation types are to be found. Where a pattern of clints and grikes can be discerned, but is overlain by vegetation comprising 25% or more of the area delimited by the interpreter, this constitutes a mosaic with grassland, heath, woodland, saltmarsh, etc., which may themselves be of national or European importance, e.g. various types of calcareous grassland, *Dryas* heathland, etc.
- where the pavement comprises shillett, few species will be able to cope with the climatic exposure, restricted rooting space or access by grazing stock.
- in addition, Newcastle University (who are monitoring limestone pavement in the Limestone Country Project in the Yorkshire Dales) have coined the term "rocks in grass" for some types of pavement which sounds very similar to the limestone pavement mosaics in the Brecon Beacons.

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[1] A set of definitions compiled by Sue Willis from the scientific literature accompanies a fuller version of this paper.

In their survey, Ward & Evans (1976) observed *"Shallower grikes lack the distinctive features of a damp and shaded microclimate and protection from grazing, which characterise the deeper grikes, and their flora does not differ markedly from the vegetation surrounding the pavement. It is the species of the deeper grikes which distinguish pavements as habitats of great floristic interest."* They limited their recording to grikes which were at least twice as deep as wide.

Definition

Mapping of limestone pavement requires some form of remote sensing, typically aerial photographs or satellite imagery, upon which potential mapping units can be delimited. Within that context, it is suggested that:

- where exposed limestone within a boundary delimited by the interpreter on aerial photographs equals or exceeds 75% by area, this constitutes limestone pavement proper. This may be regarded as "classic pavement".
- where a pattern of clints and grikes can be discerned, but is overlain by vegetation comprising 25% or more of the area delimited by the interpreter, this constitutes a mosaic with grassland, heath, woodland, saltmarsh, etc. These are the more fragmentary limestone pavements within a matrix of grassland, heath, scrub, woodland or other habitats, including shillet from the eroded or damaged pavement.

It is suggested that both are mapped as UKBAP Habitat Limestone Pavement for the purposes of this exercise; at a future date polygons of areas of "classic pavement" can be delimited.

Clearly, different interpreters will vary in their interpretation of boundaries and percentage of cover. But to make progress, we need to accept this and be pragmatic about it.

In the first instance, for the purposes of the national database, we require an overview of which areas contain limestone pavement. Thereafter, we can proceed to rationalisation.

Stephen Ward
29 October 2007

Reference

Ward SD & Evans DF. (1976). *Conservation Assessment of British Limestone Pavements based on Floristic Criteria*. Biol Conserv 9, 217-233.

APPENDIX E: Powers 'Scale of roundness' (Powers, 1953)

APPENDIX F: Geomorphological Features of Limestone Pavements

Geomorphological term + typical dimensions	*Definitions*	*Examples*
Centripetal Runnels	Pattern of solutional weathering linked to the presence of soil and/or vegetation during development (Jones, 1965).	
Clint/Flachkarren Up to several metres in length and width	An upstanding limestone block separated from the next block by weathered out joint planes termed grikes (Trudgill, 1985).	
Erratic	Rocks carried to their current locations by glacial ice, often over hundreds of kilometres from where they originated (Jones, 1965). This erratic boulder is approx. 3m wide and is located at Scar Close limestone pavement.	
Flaggy/ Laminate Bedding	Refers to clints – thinly bedded, the top bed of limestone is thin and internal horizontal fissuring may be visible which gives rise to peeling when weathered (Goldie, 1976). This example at Cam High Road, Yorkshire.	

Flaky

Refers to clints – small horizontal and sub-horizontal fissures in the limestone are frequent. Weathering results in these peeling off partially to give a scaly, flaky surface to the rock (Goldie, 1976).

Fretting/ Solution Ripples

The internal structure of the limestone is etched out to give a surface like honeycomb, also termed "honeycomb weathering" (C. Burek, 2007. pers. comm.). This view into a grike shows fretting at Farleton Knott.

Grike/Kluftkarren

Deep clefts or widened joints between clints (Sweeting, 1965). Formed by the solutional widening of near vertical joints or bedding (Gray, 2004).

Heelprints/Trittkarren

Normally 10-30cm diameter

Comparatively rare, occurring on gently inclined or shallowly stepped limestone surfaces. 'Heel' shaped indentations which may occur singly or in a down slope sequence (Ford & Williams, 2007) as illustrated from Tennant Gill limestone pavement.

Pits

<30mm across

Circular, oval or irregular hollows (Ford & Williams, 2007). Found on gentle slopes and can coalesce to give irregular, carious appearance.

Rundkarren/ Reworked Solution

400-500mm across; 30-40mm deep; 10-20m long

Runnels with rounded crests and bases, 10-50cm width and deep, normally formed under a cover of dense vegetation or organic soil (Ford & Williams, 2007).

Shillow

Degraded clint surfaces (Ford & Williams, 2007), broken up by advanced weathering or mechanical damage.

Solution Flutes/ Rills/Rillenkarren

20-40mm across; 10-20mm deep

Sharp crests between channels (shallow runnels) usually on inclined slopes, 2-3cm wide and deep. They are normal solutional features on bare limestone which is exposed to direct rainfall or snowfall. Good examples are rare in the UK (Waltham *et al.*, 1997) but these were seen at Crummack Dale.

Solution Notches

Up to 1m high & wide & 10m long

Produced by active solution where soil abuts against projecting rock giving rise to curved incuts (C. Burek, 2007. pers. comm.).

Solution Pans/ Kamenitzas

10-500mm deep; 0.03-3m wide

Solution basin, circular, sub-circular or elliptical. Edges may be fluted or smooth. Usually floored by a thin layer of soil, vegetation or algal remains (Ford & Williams, 2007).

Solution Pipes

1m across
2-5m deep

Usually become narrower with depth (H. Goldie, 2008. pers. comm.).

Solution Runnels/ Rinnenkarren

Larger than rillenkarren, sharp crest but bases more rounded, up to 50cm deep, formed on bare rock (Ford & Williams, 2007). This photograph taken at The Rakes, Hutton Roof.

Undercut Solution Runnels/Hohlkarren

400-500mm across
300-400mm deep
10-20m long

Like runnels but become larger with depth. Recession at depth probably associated with accumulation of humus or soil which keeps sides at base constantly wet (C. Burek, 2007. pers. comm.).

References:

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Goldie, H. (1976). *Limestone pavements with special reference to North West England.* Unpublished DPhil, St.Hugh's College, Oxford.

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Jones, R. J. (1965). Aspects of biological weathering of limestone pavement. *Proceedings of the Geologists' Association, 76*(4), 421-433.

Sweeting, M. M. (1966). *The weathering of limestone with particular reference to the Carboniferous limestone of Northern England.*

Trudgill, S. T. (1985). Field observations of limestone weathering and erosion in the Malham district, North Yorkshire. *Field Studies, 6*(2), 201-236.

Waltham, A. C., Simms, M. J., Farrant, A. R., & Goldie, H. S. (1997). *Karst and Caves of Great Britain* (Vol. 12). London: Chapman & Hall.

Sue Willis, Geomorphology Checklist

APPENDIX G: Soil Texture Chart (Black, 1997)

APPENDIX H: Pavement Formation Assessment (Ellis, 2007)

APPENDIX I: Plant species recording proforma

Site Name: **Botanists:**

Date:

Acer pseudoplatanus	Sycamore			*Linum cartharticum*	Fairy flax		
Actaea spicata	Baneberry	A spp.		*Lonicera periclymenum*	Honeysuckle		
Allium ursinum	Ramsons			*Lotus corniculatus*	Bird's-foot Trefoil		
Anemone nemorosa	Wood anemone			*Melica nutans*	Mountain melick	B spp.	
Angelica sylvestris	Angelica			*Mercurialis perennis*	Dog's mercury		
Anthoxanthum odoratum	Sweet vernal grass			*Mycelis muralis*	Wall lettuce	B spp.	
Arabis hirsuta	Hairy rock cress	B spp.		*Oxalis acetosella*	Wood-sorrel		
Arrhenatherum elatius	False Oat Grass			*Paris quadrifolia*	Herb paris	B spp.	
Arum maculatum	Lords and ladies	B spp.		*Phyllitis scolopendrium*	Hart's-tongue		
Asplenium adiantum-nigrum	Black spleenwort			*Pimpinella saxifraga*	Burnet-saxifrage		
Asplenium ruta-muraria	Wall rue			*Polygonatum odoratum*	Angular Solomon's seal	A spp.	
Asplenium trichomanes	Maidenhair spleenwort			*Polypodium vulgare*	Common polypody		
Asplenium viride	Green spleenwort	B spp.		*Polystichum aculeatum*	Hard shield-fern	B spp.	
Athyrium felix-femina	Lady fern			*Potentilla sterilis*	Barren strawberry		
Briza media	Quaking grass			*Primula vulgaris*	Primrose		
Campanula rotundifolia	Harebell			*Prunella vulgaris*	Selfheal		
Cardamine hirsuta	Hairy bitter-cress			*Prunus padus*	Bird Cherry		
Cardamine impatiens	Narrow-leaved bittercress			*Prunus spinosa*	Blackthorn		
Carex digitata	Fingered sedge			*Pteridium aquilinum*	Bracken		
Carex flacca	Glaucous Sedge			*Rhamnus cathartica*	Common buckthorn	B spp.	
Carex nigra	Common Sedge			*Ranunculus acris*	Meadow buttercup		
Carex panicea	Carnation Sedge			*Ribes spicatum*	Downy currant	A spp.	
Centaurea nigra	Knapweed			*Ribes uva-crispa*	Gooseberry		
Ceterach officinarum	Rusty-back fern			*Rosa canina*	Dog-rose		
Chamerion angustifolium	Rosebay willowherb			*Rubus fruticosus*	Bramble		
Cirsium arvense	Creeping thistle	neg		*Rubus idaeus*	Raspberry		
Cirsium heterophyllum	Melancholy thistle	B spp.		*Rubus saxatilis*	Stone bramble		
Cirsium vulgare	Spear thistle	neg		*Salix caprea*	Goat willow		
Convallaria majalis	Lily-of-the-valley	B spp.		*Salix cinerea*	Grey willow		
Corylus avellana	Hazel			*Sambucus nigra*	Elder		
Crataegus monogyna	Hawthorn			*Sanicula europaea*	Sanicle		
Cystopteris fragilis	Brittle bladder-fern	B spp.		*Saxifraga tridactylites*	Rue-leaved saxifrage		
Dactylis glomerata	Cocksfoot			*Scabiosa columbaria*	Small Scabious		
Danthonia decumbens	Heath grass			*Scrophularia nodosa*	Common figwort		
Dryas octopetala	Mountain avens			*Senecio jacobaea*	Ragwort	neg	
Dryopteris carthusiana	Narrow buckler fern			*Sesleria caerulea*	Blue Moor Grass		
Dryopteris dilitata	Broad buckler fern			*Silene dioica*	Red Campion		
Dryopteris filix-mas	Common male fern			*Solidago virgaurea*	Goldenrod		
Dryopteris submontana	Rigid buckler fern	A spp.		*Sonchus arvensis*	Perennial sow-thistle		
Epilobium montanum	Broad leaved willow-herb			*Sorbus aria*	Common whitebeam		
Epipactis altrorubens	Dark-red helleborine	A spp.		*Sorbus aucuparia*	Rowan		
Euphrasia nemorosa	Eyebright			*Stachys sylvatica*	Hedge woundwort		
Festuca ovina	Sheep's fescue			*Succisa pratensis*	Devil's-bit Scabious		
Festuca rubra	Red fescue			*Taraxacum officinalis*	Dandelion		
Filipendula ulmaria	Meadowsweet			*Taxus baccata*	Yew	B spp.	
Fragaria vesca	Wild strawberry			*Teucrium scorodonia*	Wood sage		
Fraxinus excelsior	Ash			*Thalictrum minus*	Lesser meadow-rue	B spp.	
Galium aparine	Cleavers			*Thymus polytrichus*	Wild thyme		
Galium odoratum	Woodruff			*Trollius europaeus*	Globeflower		
Galium sterneri	Limestone bedstraw			*Ulmus glabra*	Wych elm		
Geranium robertianum	Herb robert			*Urtica dioica*	Nettle	neg	
Geranium sanguinium	Bloody crane's-bill	B spp.		*Valeriana officinalis*	Common Valerian		
Geranium sylvaticum	Wood crane's-bill			*Veronica chamaedrys*	Germander Speedwell		
Geum rivale	Water avens			*Viburnum opulus*	Guelder-rose		
Geum urbanum	Wood avens			*Vicia cracca*	Tufted vetch		
Gymnocarpium robertianum	Limestone fern	A spp.		*Vicia sepium*	Bush vetch		
Hedera helix	Ivy			*Viola hirta*	Hairy violet	B spp.	
Helianthemum chamaecistus	Common rock-rose			*Viola riviniana*	Common Dog Violet		
Heracleum sphondylium	Hogweed						
Hieracium sp.	Hawkweed						
Holcus lanatus	Yorkshire fog						
Hypericum montanum	Pale St John's wort						
Ilex aquifolium	Holly						
Inula conyzae	Ploughman's-spikenard	B spp.					
Juniperus communis	Juniper	B spp.					
Lathyrus pratensis	Yellow meadow vetchling						
Leontodon hispidus	Hairy hawkbit						

Bryophytes:

Atrichum undulatum	
Brachythecium rutabulum	
Bryum capillare	
Climacium dendroides	
Conocephalum spp	
Ctenidium molluscum	
Dicranum scoparium	
Ditrichum gracile	
Encalypta streptocarpa	
Fissidens spp.	
Grimmia spp	
Homalothecium spp.	
Hylocomium splendens	
Hypnum cupressiforme agg	
Kindbergia (Eurhynchium) praelonga	
Lophocolea bidentata	
Mnium hornum	
Neckera complanata	
Neckera crispa	
Orthotrichum anomalum	
Pellia epiphylla	
Plagiomanium undulatum.	
Polytrichum formosum	
(Pseudo)Scleropodium purens	
Rhytidiadelphus squarrousus	
Schistidium apocarpum	
Thamnobryum spp	
Thuidium tamariscinum	
Tortella tortuosa	
Weissia spp.	
Algae	

Emergent spp:

	Species	Height - cm
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Notes:

APPENDIX J: Grazing and Management Interview

Pavement Name:				
Date:				
Name of Interviewee:				
Contact details:				
Notes:				
		Yes	**No**	**Comments**
Grazing				
Type	Sheep Cattle - give breed Sex / Age / Background			
Timing	Jan / Feb / March / April / May / June / July / Aug / Sept / Oct / Nov / Dec			
Density				
Shepherding				
Management	Management agreement in place? Date agreement started:			
Have any of these taken place on the pavement?	-Tree / Scrub / Bracken removal			
	-Sycamore spraying			
	-Ragwort / Thistle / Nettle removal/treatment			
	-Grazing exclusion			
	-Fencing type/height/reason/date/efficacy			
	-Rabbit / Deer control			
	-Planting			
	-Coppicing			
	-Application of Manure / Fertilizer / Lime / Weedkiller			
	-Removal of stone / Infilling grikes			
Owner noticed changes?				

APPENDIX K: Mollusc species recorded on the 11 limestone pavements

Species name	Abbrev. name	Limestone pavement name and date of survey										
		IBCOLT 23.04.08	IBCRUM 31.07.08	IBSCAR 21.06.08	IBSUL 31.07.08	KWPDH 10.09.08	KWPOX 31.05.08	MACBOR 19.03.08	MACBW 19.05.08	MACLG 19.05.08	MACTG 10.09.08	YORCAM 03.06.08
Abida secale secale (Draparnaud, 1801)	Abidseca	0	0	2	0	0	0	0	0	0	0	0
Acanthinula aculeata (O.F.Müller, 1774)	Acanacul	0	0	2	0	0	0	0	2	0	0	0
Acicula fusca (Montagu, 1803)	Acicfusc	0	0	2	0	0	0	0	0	0	0	0
Aegopinella nitidula (Draparnaud, 1805)	Aegoniti	2	0	4	0	0	0	2	2	0	0	0
Aegopinella pura (Alder, 1830)	Aegopura	2	0	2	0	0	1	1	4	0	0	0
Arianta arbustorum arbustorum (Linnaeus, 1758)	Ariaarbu	4	0	2	0	4	4	0	2	0	0	0
Arion ater (Linnaeus, 1758)	Arioater	2	1	2	2	2	2	2	4	0	2	4
Arion circumscriptus (Johnston, 1828)	Ariocirc	2	0	2	0	0	0	4	2	0	0	1
Arion fasciatus (Nilsson, 1822)	Ariofasc	0	0	2	0	0	0	0	0	0	0	0
Arion silvaticus (Lohmander, 1937)	Ariosilv	1	0	0	0	0	0	0	0	0	0	0
Arion distinctus (Mabille, 1868)	Ariodist	4	0	0	0	0	0	0	2	0	0	0
Arion intermedius (Normand, 1852)	Ariointe	2	1	2	2	0	0	2	2	1	0	4
Arion subfuscus (Draparnaud, 1805)	Ariosubf	2	0	0	0	2	0	0	0	0	0	2
Azeca goodalli (A. Férussac, 1821)	Azecgood	4	0	0	0	0	0	0	0	0	0	0
Carychium minimum O.F.Müller, 1774	Carymini	4	0	2	0	0	0	1	0	0	0	0
Carychium tridentatum (Risso, 1826)	Carytrid	4	2	4	2	0	1	0	0	0	0	0
Cepaea hortensis (Muller, 1774)	Cepahort	0	0	0	0	0	0	0	0	0	2	0
Cepaea nemoralis nemoralis (Linnaeus, 1758)	Cepanemo	1	0	4	0	0	4	0	4	4	0	0
Clausilia dubia suttoni (Westerlund, 1881)	Claudubi	3	1	4	4	4	0	4	3	4	4	0
Clausilia bidentata bidentata (Ström, 1765)	Claubide	4	0	4	0	0	4	0	4	4	0	0
Cochlicopa lubrica (O.F.Müller, 1774)	Cochlub1	4	2	4	4	2	4	1	4	0	2	4
Cochlicopa lubricella (Rossmässler, 1834)	Cochlub2	2	2	4	0	0	4	2	4	0	0	1
Cochlodina laminata (Montagu, 1803)	Cochlami	0	0	0	0	0	3	0	0	0	0	0
Columella aspera (Walden, 1966)	Coluaspe	1	0	2	0	0	0	0	0	0	0	0
Columella edentula (Draparnaud, 1805)	Colueden	1	0	2	0	0	0	0	0	0	0	0
Deroceras laeve (O.F.Müller, 1774)	Derolaev	0	0	2	0	0	0	0	0	0	0	0
Deroceras reticulatum (O.F.Müller, 1774)	Deroreti	0	0	4	2	2	4	2	4	0	2	4
Discus rotundatus rotundatus (O.F.Müller, 1774)	Discrotu	4	2	4	4	4	4	4	4	4	4	1

Species name (cont.)	Abbrev. name	Limestone pavement name and date of survey										
		IBCOLT 23.04.08	IBCRUM 31.07.08	IBSCAR 21.06.08	IBSUL 31.07.08	KWPDH 10.09.08	KWPOX 31.05.08	MACBOR 19.03.08	MACBW 19.05.08	MACLG 19.05.08	MACTG 10.09.08	YORCAM 03.06.08
Euconulus fulvus (O.F.Müller, 1774)	*Eucofulv*	4	0	2	0	2	1	0	0	0	0	0
Galba truncatula (O.F.Müller, 1774)	*Galbtrun*	0	0	2	0	0	0	0	0	0	0	0
Helicigona lapicida lapicida (Linnaeus, 1758)	*Helilapi*	0	0	0	0	0	0	3	0	4	0	0
Lauria cylindracea (Da Costa, 1778)	*Laurcyli*	4	4	4	4	4	4	4	3	4	4	0
Merdigera obscura (O.F.Müller, 1774)	*Merdobsc*	0	4	4	0	0	4	0	4	4	0	0
Nesovitrea hammonis (Ström, 1765)	*Nesohamm*	1	0	2	4	0	1	0	0	2	0	0
Oxychilus alliarius (Miller, 1822)	*Oxycalli*	4	4	4	4	4	4	4	4	2	4	0
Oxychilus cellarius (O.F.Müller, 1774)	*Oxyccell*	2	2	0	0	2	4	1	4	2	4	0
Pisidium casertanum (Poli, 1791)	*Pisicase*	0	0	2	0	0	0	0	0	0	0	0
Punctum pygmaeum (Draparnaud, 1801)	*Puncpygm*	0	0	0	1	0	0	0	0	0	0	0
Pyramidula pusilla (Vallot, 1801)	*Pyrapusi*	0	4	4	4	4	1	4	3	4	4	4
Trochulus hispidus (Linnaeus, 1758)	*Trochisp*	1	0	0	0	2	4	0	4	4	0	4
Trochulus striolatus abludens (Locard, 1888)	*Trocstri*	4	4	4	4	0	4	4	4	4	0	0
Vallonia excentrica (Sterki, 1893)	*Vallexce*	0	0	0	0	1	1	0	0	0	1	0
Vertigo pygmaea (Draparnaud, 1801)	*Vertpygm*	0	0	2	2	0	0	0	0	0	0	0
Vertigo substriata (Jeffreys, 1833)	*Vertsubs*	0	0	2	0	0	0	0	0	0	0	0
Vitrea contracta (Westerlund, 1871)	*Vitrcont*	4	2	4	4	4	2	4	4	4	4	4
Vitrea crystallina (O.F.Müller, 1774)	*Vitrcrys*	4	0	0	0	4	1	0	0	0	0	1
Vitrea subrimata (Reinhardt, 1871)	*Vitrsubr*	0	2	2	4	0	1	2	1	0	2	1
Vitrina pellucida (O.F.Müller, 1774)	*Vitrpell*	2	0	2	0	0	0	0	4	4	0	0