Calluna vulgaris regeneration on upland moorland post-wildfire.

Jacqueline Anne Gilbert
BSc (Hons) Environmental Management

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ABSTRACT

Upland heather moorland is often subjected to wildfires, particularly in drought years, which destroy all vegetation, seed bank and surface peat. Post-fire management of liming, fertilising and seeding with grass species and *Calluna vulgaris* (ling heather), in addition to natural regeneration, often fails to fully re-vegetate the bare burnt peat, leading to erosion and degraded sites.

Here, two sites were under investigation: Darwen Moor that suffered a severe fire in 1995, and a moor overlooking Stalybridge, Tameside, burnt in 1980. Both burnt areas received similar post-fire management.

After a full vegetation survey of Darwen Moor, with data analysed using Two-way species indicator analysis (Twinspan), permanent quadrats were established within representative areas of identified vegetation sub-communities. Twice yearly surveys (spring and autumn) were undertaken within areas defined by these quadrats.

Results of vegetation survey showed regeneration of *C. vulgaris* on burnt sections of Darwen moor had increased from 18% to 38%, (2000-2005), and had become the dominant species, with only 3% of the burnt moor remaining unvegetated. Vegetation succession was not advancing unidirectionally with increasing variation between samples of the same sub-community. This was in contrast to the Stalybridge site that remained unvegetated (77%) twenty-five years after wildfire.

Survey data were collected using both digital photography and point quadrat survey. Pre-monitoring investigation showed no significant difference between data collected by these techniques.

Experiments were undertaken to assess aspects of *C. vulgaris* seed dispersal and viability. Seed-trap experiments using transplanted *C. vulgaris* suggested that few seeds are being dispersed into degraded sites, whilst datalogger evidence showed poor germination opportunity for *C. vulgaris* seeds on moorland post-wildfire.

C. vulgaris seeds were shown to germinate and grow on moorland peat in controlled conditions, although they rapidly became unviable when exposed to drought conditions. Use of a polyacrylamide gel to enhance environmental conditions for sown grass species showed early increased ground cover but failed to show any significant increase after 14 months.

Accepted upland moorland revegetation management post-wildfire is reviewed and from experimental results, additional management techniques are suggested.

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Species List

Moorland research related species

	Common Name
Agrostis castellana	Highland Bent
Aster novi-belgii	Michaelmas daisy
Calluna vulgaris	Heather, Ling
Chamerion angustifolium	Rosebay willowherb
Cladonia spp.	
Deschampsia flexuosa	Wavy hair-grass
Erica tetralix	Cross-leaved heath
Eriophorum angustifolium	Common cotton grass
Eriophorum vaginatum	Harestail cotton grass
Festuca rubra, sub-*spp. commutata*	Chewings fescue
Festuca ovina	Sheeps fescue
Hymenoscyphus ericae	Ericoid mycorrhizal fungi
Molinia caerulea	Purple moor grass
Polytrichum commune	
Salix spp.	Willow
Sorbus aucuparia	Rowen, mountain ash
Sphagnum spp.	
Vaccinium myrtillus	Bilberry

Research method related species

Acer pseudoplatanus	Sycamore
Eucalyptus	
Gleditsia triacanthos	Common honeylocust
Gymnocladus diocia	Kentucky coffeetree
Robinia psuedoacacia	Black locust

Non-plant species

Lapopus lagopus	Red Grouse
Lochmaea suturalis	Heather beetle

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Dedicated to Posy and Podge, and all others who enrich our lives.

1.0 CHAPTER 1

INTRODUCTION AND AIMS.

1.1 BACKGROUND TO THIS STUDY.

Wildfires on moorland, particularly in drought years are not uncommon, and their effects may prove severe and long lasting. Fires that burn for a long period or are too hot destroy the stands of *Calluna vulgaris (L) Hull*, burn deeply into the underlying organic horizons and may destroy the soil seedbank. Natural regeneration of vegetation is often slow and many badly burnt sites remain bare for decades after wildfires (Radley 1965, Maltby *et al.* 1990, Gilchrist *et al.* 2004).

1.1.1 Heather Moorland.

Upland heather moorland is a habitat, found above 300m, with a dominant covering of *C. vulgaris*. The lower limit of 300m above sea level (a.s.l.) is usually defined by enclosed agricultural fields, but variations occur particularly in the north-west of the UK. Land below this sub-montane zone and with at least 10% cover of *C. vulgaris* is classified as lowland heath. The montane zone, which lies above the sub-montane zone of upland moor, occurs at 600-700m a.s.l. and contains some growth of *C. vulgaris*. Virtually all heather moorland in the UK occurs within the sub-montane zone (Thompson *et al.* 1995). This distinctive landscape of upland heather moorland is found in the north, west and south west of the UK, Ireland and in the extreme western and southern parts of Norway. Britain offers the best representation of this habitat (Thompson *et al.* 1995).

The formation of wild open upland moorland in Britain and the decline of the forest that once occupied this land are frequently associated with Bronze Age human settlements and land cultivation. However, there is some evidence of climatic change to a cooler more oceanic regime about 500 B.C. that favoured moorland as opposed to trees (Gimingham 1972).

Research on upland moorland is important as moorland plant communities are of international importance to nature conservation, and protected under the conservation of natural habitats of fauna and flora EC (1992) Directive 92/43/EEC. Forty-six bird species are known to use heather moorland for breeding or feeding, eleven of which are listed under Annex 1 of the European Directive on the 1979 conservation of Wild Birds, EC Directive 79/409/EEC (The Moorland Association 2007). Peatlands worldwide also hold up to 24% of stored soil carbon (Friends of the Earth 1992), and moorland may be of economic importance to local communities.

1.1.2 *Calluna vulgaris* ecology.

C. vulgaris is usually the dominant plant species on heathland and moorland, but can also be found in acidic pastures, sandstone quarries and on outcrops and cliffs (Grime *et al.* 1996). This evergreen dwarf shrub is relatively short-lived (normally under 30 years), with a flowering period from August to September, with seeds shed from September onwards, although some may over-winter attached to the plant. The seeds, with dimensions of 0.55–0.65mm x 0.35-0.45mm, have a mass of approx. 0.025g, are elliptic in shape and are yellowish-red (Fagundez and Izco 2004). Seeds are held in a capsule and are wind dispersed. Number of seeds in each capsule range from 0-41 (overall mean 10 seeds) (Legg *et al.* 1992), 2-37 (Traynor 1995) whilst Miller and Cummins (2987) suggest 14-19 seeds at 30m a.s.l. Numbers of seeds produced range from 1 to 2.5 million per square metre in a vigorous stand (Gimingham 1989, Mallik *et al.* 1984) although number of capsules and seeds are affected by size and age of plant and environmental growth conditions. Seeds also have the ability to survive for up to 100 years within the soil seed-bank if conditions are favourable (Miller and Cummins 1987). Gimingham (1989) also suggests that the ability of *C. vulgaris* to dominate extensive areas may be that it has some of the characteristics of pioneer or 'r-selected' plants, for example a high reproductive capacity and readily dispersed seeds.

C. vulgaris seeds may germinate between eight to fourteen days (Gimingham 1972) with a ideal germination temperature of 10-28°C (Grime *et al.* 1996). *C. vulgaris* seeds can germinate and seedlings become established in a wide range of soil types and soil moisture regimes conditions, although wet conditions increase germination (Bannister 1964a).

C. vulgaris grows in a well recognised cyclical form: -

i. Pioneer phase: where heather colonises the gaps amongst old dead heather stems, this usually lasts for 3-6 years.
ii. Building phase: where the plant produces an even half-spherical form, 7-13 years.
iii. Mature phase: plant become leggy and woody, centre begins to open up, 12-28 years
iv. Degenerate phase: plant very prostrate large gaps within the vegetation, 16-29 years.

Adapted from Gimingham (1972)

C. vulgaris is the most important species found on moorland in Britain and provides valuable food for hill sheep and red grouse (*Lapopus lagopua*), particularly during the first 15-20 years of life, when its canopy is increasing. Leaves are low in phosphorus (P) and calcium (Ca), but often contain relatively high amounts of manganese (Mn) and aluminium (Al) (Grime *et al.* 1996).

1.1.3 Management of *Calluna vulgaris.*

The management techniques used to keep the moorland open, free from trees (in an arrested successional state) and to produce young shoots of heather for sheep, grouse or deer has been muirburn. Muirburn is a controlled method of burning the vegetation in a systematic and rotational way that produces a mosaic of different ages and size of heather. This juxtaposition of *C. vulgaris* at different ages is ideal cover and food for grouse. Properly conducted, muirburn is followed by rapid regeneration of plants either from the rootstock of the old burnt plant or from the seed-bank within the litter.

The length of burning rotation is rarely less than 7-8 years and may be 15-20 years, depending on altitude, soil type, aspect, exposure, grazing pressure and climatic conditions of the moor, all which affect growth rate. There is usually enough plant material for a good clean burn by the time the heather reaches a height of 20cm but it should be burnt before it becomes as tall as 30cm. Old leggy heather may not sprout from the rootstock and regeneration is then dependent on the seed bank, when regeneration will take longer. A muirburn fire has to be hot enough to remove the vegetation but not too hot to destroy the basal buds or scorch the seeds in the upper layer of soil. Fires are usually burnt in the direction of the wind to ensure the fire burns the heather quickly and do not become too hot. Management by this method is undertaken between 1st October and 15th April (Muirburn Working Party 1977, MAFF 1994). Temperatures in a managed heath fire have been recorded to be as high as 840°C although those most frequently recorded were between 300°C and 500°C (Whittaker 1961).

1.1.4 Damage from wildfires.

Ecosystems in which fire is a common hazard can be considered as 'fire-adapted', for example Australian *Eucalyptus* seeds often need fire to stimulate germination (Rizvi and Rizvi 1992). Woody plants in fire-prone communities have developed various adaptations for survival in wildfires. Adult plants have three typical responses: -

i. have insulating bark,
ii. are able to re-sprout from dormant buds
iii. or die allowing seeds to recolonise the bare soil after the fire (Rizvi and Rizvi 1992).

C. vulgaris is well adapted for muirburns as the fires leave the roots intact and buds on the basal stem ready for regrowth. The seedbank within the soil is protected under the litter and able to germinate after the fire. However, deeply burnt areas where all the vegetation has been removed can almost be classified as primary successional sites as they have very few characterises of the 'old site' (Maltby *et al.* 1990). Seeds within the soil can be killed by heat, as exposures to temperatures that exceed 200°C are lethal. Below 200°C the time of exposure to heat determines how lethal the temperature will be i.e. 120°C for 30 seconds shows a depression of germination, but this response occurs after 20 seconds at 160°C. Charring of *C. vulgaris* seeds is lethal even if accompanied by non-lethal temperatures. Charring occurs by direct contact with either flames or smouldering litter (Whittaker and Gimingham, 1962).

Studies on badly burnt moorland suggest that the biological, physical and possible chemical changes induced by the fire and subsequent exposure to the atmosphere result in the development of three distinct crust types. Maltby *et al.* (1990) describe these crusts as:-

i. A 'hard' crust on charred peat columns: 10 –20mm thick and easily detached horizontally from underlying peat but difficult to break up by hand.
ii. A 'soft' crust on intact peat surfaces: 5-10mm thick, easily detached horizontally from underlying peat and easily broken up by hand into small fragments.
iii. A fragile, mineral crust on exposed mineral soil and ash developed by wetting/drying and raindrop impact: less than 2mm and easily broken up by hand.

Fires that exceed 300°C have a significant effect on soil properties with a loss of organic matter content, a decrease in cation exchange capacity and in exchangeable bivalent cation concentrations. Nutrients are lost in the smoke, i.e. carbon, sulphur and nitrogen, whilst some are present in ash deposited on the ground; some of these deposited nutrients may then be leached by rainwater (Forgeard and Frenot 1996).

Erosion of bare peat left after wildfire is a problem and sites that remain bare can often develop deep eroded gullies (Tallis 1987). Many peatland soils are in close proximity to urban or industrial areas, which have contaminated with anthropogenically derived, atmospherically deposited toxic heavy metals. Any erosion following accidental wildfire will release these contaminants; Pb has been shown to be released in significant quantities into the fluvial system post wildfire (Rothwell *et al.* 2007).

1.1.5 Methods of management – post-wildfire.

Numerous trials to establish best practice for post-fire management of moorland were conducted in the 1970s and 1980s, which followed many large wild fires on the North Yorkshire Moors and in the Peak District (Tallis and Yalden 1983, Anderson and Radford 1988). It is from this period that most literature on English moorland wildfires and on vegetation regeneration post-wildfire was published.

Small trials, often with $1m^2$ size plots given various treatments and seeded with grass species and *C. vulgaris,* formed the preliminary investigations. Examples of trials are presented in Table 1.0.

Table 1.0 Preliminary trials of management techniques for restoring vegetation on degraded moorland. Adapted from – Peak District Moorland project, A National Review of Moorland Restoration Techniques (Anderson and Radford 1988) and from the North York Moors National Park (NYMNPC 1980 and 1986).

Location	Date	Technique	Results
Glaisdale Moor 1,300 acres (526ha)	1976	Trial Plots – cut heather brush laid on ground and secured with wire netting.	Seedlings produced, grazed by grouse.
Cannock Chase Fire 1976	1977	Grass seeds. No lime or fertiliser. Field trials - establishment of heather in grass mixes.	*Deschampsia flexuosa* most suited. Little heather from any seed source. Thought to be a consequence of seeds not coming into contact with ground and drying out.
Glaisdale Moor	1979	Series of experiments – Various seeds, addition of fertiliser. Rotavating and rolling. Fencing.	*D. flexuosa* able best to tolerate the conditions. Heather restricted by availability of seed. Fencing is beneficial.

Following these preliminary experiments regeneration trials were conducted, although results were often mixed, these trials did help to establish best practice. Examples of these trials are presented in Table 1.1.

Table 1.1. Examples of Moorland regeneration trials conducted after preliminary trials to establish best practice. Adapted from Peak District Moorland Management Project Phase II report: Re – Vegetation Trials, (Tallis and Yalden 1983) and from the North York Moors National Park (NYMNA 2003).

Location	Date	Technique	Results
Holme Moss	1984	Hydra-seeding *C. vulgaris* Lime and fertiliser	*C. vulgaris* increased as grass declined.
Burbage Moor	1986	Heather and grass seeds	Increased heather 11-54% Bare peat 10 – 4% (1988 – 1992)
Kinderlow	1987	*C. vulgaris* and grass seeds, Lime and fertiliser	Increased *C. vulgaris* 1987-1991. Increased bare peat as grass declined
Peaknage	1992	*C. vulgaris* and grass seed. Peat surface mechanically disturbed	Increased *C. vulgaris* in areas of peat disturbance
Glaisdale	1984-1993	Nurse grass species and cut heather.	Increased cover of *C. vulgaris*

These regeneration trials, which started in 1979, in addition to subsequent reports, resulted in many conclusions, some of which relate to this research:-

1. Revegetation of moorland soils is very difficult.
2. To restore grass cover, commercial seed sources will suffice, but regular lime and fertiliser applications are necessary.
3. Any treatment can be ruined by chance stochastic events, sudden floods, droughts, fire, strong winds, severe snowfall, this failure in one treatment on one occasion should not necessarily be regarded as final.
4. The detailed mechanisms of the factors limiting re-vegetation are not fully understood.
5. The substantial costs and inaccessibility thwart desirable restoration.

(Adapted from Tallis and Yalden 1983, Anderson *et al.* 1997).

Large regeneration projects have been carried out, not only to restore moorland after wildfire but also to repair moorland that has been damaged from mineral extraction, pipeline lying, re-instatement of *C. vulgaris* on farmland and on bare peat from erosion and trampling (Putwain and Rae 1988, Putwain 1992, Anderson *et al.* 1997). The regeneration of Flylingdales Moor, which is part of North York Moors, is an example of regeneration using many trialled techniques. Following a wildfire in 2003 that severely damaged 250ha of Fylingdales Moor, management was to sow nurse grass species in 2003-2004 with heather seed and brash spread in 2004-2006. Results show some grass species (*A. castellana* and *D. flexuosa*) have established very well, also regeneration of moorland vegetation including *C. vulgaris* is well distributed across the site (Manners 2007, NYMNPA 2007, Pickering 2007).

Techniques of applying lime, fertiliser and seeding with nurse-species are currently still in use although this method is often used in a combination of many regeneration methods. One of the largest usages has been in the Peak District by 'Moors for the Future Partnership', as part of a £47 million investment from the Lottery Fund. Geojute-textiles and heather brash have also been used to try to stabilise peat surfaces. For example, 640 tonnes of heather brash and 70,000m^2 of geotextiles were applied during the autumn and winter of 2004/5 on Bleaklow and Kinder Scout (Moors for the Future Partnership 2007). To date, there are no published results on the effectiveness of this management (Walker 2007, per.comm.), although good results were presented at the Environmental Processes Research Group Conference in June 2007.

1.1.6 Re-growth of *Calluna vulgaris* post- wildfire.

Re-establishment of *C. vulgaris* through natural regeneration has been reported to be slow (Radley 1965) and post wildfire management often failed to re-vegetate a damaged and degraded site (Tallis and Yalden 1983, Anderson *et al.* 1997). Failed regenerative management on moorland post wildfire often goes unreported and much of this evidence comes from gamekeepers and moorland managers; something that has occurred on the sites included in the current study.

The remaining peat surface, following a severe wildfire, may have physical properties that inhibit germination of seed and growth of vascular plants. Before a fire, the organic matter such as partially decomposed leaves, twigs and lichens increases the water retention property of the soil, which helps seedling regeneration (Mallik *et al.* 1988). Following a fire, the blackened surface of the organic matter may become an unsuitable medium for seed germination and plant growth. The exposures of this burnt surface to many physical factors, for example, precipitation, wind and drought lead to poor seedbed conditions. Gimingham (1972) also suggests that after only two weeks of exposure to a desiccating atmosphere, subsequent germination is delayed.

The formation of a surface crust tends to form a hard barrier that is resistant to re-wetting and often heaves away from the underlying soils, breaking the hydraulic continuity (Maltby *et al.* 1990). The crust may also form a hard barrier into which seedling roots cannot penetrate (Marschner 1995).

The unvegetated burnt surface, which consists of fine mineral and organic material, is liable to movement by wind and water action. Maltby *et al.* (1990) suggest that movement of ash and fine peat granules by wind action is particularly extensive in the autumn immediately after the fire and in the following summer. Frost action may also assist in separation of the top layer of crust away from the underlying peat surface. These climatic elements help to cause surface instability and further poor seedbed conditions. Areas affected by severe fires have shown no vascular plant establishment for long periods and such areas show progressive and accelerated erosion that often forms large gullies (Maltby 1980).

In the year following a severe fire, a covering of lichens and algae may develop (Shields and Durrell 1964, Gimingham 1972), which have been shown to increase the germination and establishment of some vascular plants by improving the water-retaining properties and surface stability (Shields and Durrrell 1964). However, Legg *et al.* (1992) have shown lichens and algae inhibit germination of *C. vulgaris* seeds. Hobbs (1985) has also shown an inhibition of *C. vulgaris* germination by *Cladonia* species.

Changes in nutrient status of peat following fires may have significant effects on the growth of *C. vulgaris* seedlings. Gore and Godfrey (1981) claim that the inherent infertility of eroding peat is important in preventing natural recolonisation. However Legg *et al.* (1992) showed that growth of *C. vulgaris* seedlings in untreated trial plots is possible. Transplant experiments also indicate that residual peat is adequate for normal shoot growth even in the absence of additional macro-nutrients (Legg *et al.* 1992).

Natural regeneration of bare peat sites will depend on the ability of surrounding heather stands to produce seeds in sufficient numbers and in the ability of the seeds to spread to the awaiting site. In a seed-shedding study in north-eastern Scotland the total number of seeds per square metre deposited in stands of *C. vulgaris* in its four growth phases were: pioneer, 18,910; building, 169,010; mature, 198,580; degenerate, 33,900 (Bullock *at al.* 1994). On lowland heath Traynor (1995) suggested the productivity of *C. vulgaris* to be 880,000 m^{-2}.

Seeds of *C. vulgaris* dispersed by the wind are reported to be spread for 100m or more across open moorland; however most are deposited within one metre of the parent plant (Legg *et al.* 1992). This was confirmed in a trial on grassland with a transplanted heather plant where the majority of seeds were trapped within one metre, with only very few seeds collected up to 80m away from the plant (Bullock and Clarke 2000). Size of a degraded site may also limit colonisation of plants due to slow immigration of propagules (Miles 1979). The regeneration of *C. vulgaris* on burnt moorland may also be limited by available microsites where seeds are protected from adverse environmental conditions. Recruitment in plant populations has been shown to be limited by the availability of microsites and by the availability of seed (Eriksson and Ehrlen 1992).

The rate of recolonisation by mycorrhizal fungi will also have an effect on the growth of *C. vulgaris*, as growth and the ability to compete with other plant species have been shown to increase when mycorrhizal fungi are present (Kerley and Read 1998, Genney *et al.* 2000).

C. vulgaris seeds are light sensitive and are inhibited by darkness (Gimingham 1972) and may not germinate under the canopy of existing plants or where litter or grass from site regeneration management is too high (Gunnlaugsdottir 1982).

Where post-wildfire management has established vegetation cover there is little evidence from literature of the long-term succession of vegetation on upland moorland in the UK, or whether the provision of nurse species from post-wildfire management facilitates regeneration of *C. vulgaris.*

1.2 RESEARCH AIMS.

Damage from moorland wildfires can be extremely varied. A quick fire, similar to a management burn, may only remove the above-ground vegetation leaving the seed-bank intact with germination of these seeds and early seedling growth of *C. vulgaris* taking only a few months. Other wildfires may completely destroy all vegetation, the seed bank and burn into the underlying peat. This research concentrates on the latter, the regeneration of *C. vulgaris* on upland moorland after a severe wildfire.

The two upland moorlands used in this research have a long history of management for grouse with the customary muirburn management of *C. vulgaris*. The vegetation on both sites has been dominated by *C. vulgaris* and this is the desired vegetation. The ability of *C. vulgaris* to recolonise the burnt peat from post-wildfire management or by natural regeneration from dispersed seed is fundamental if this single species dominated environment is to be achieved. Therefore, this research concentrates on regeneration of *C. vulgaris* on severely burnt moorland, also the properties of bare burnt peat and environmental conditions of burnt upland moorland post-wildfires that may hinder regeneration of *C. vulgaris*. In this context there are two main research aims.

The first aim was to investigate the potential for post-wildfire management using liming, fertilising and sowing nurse-species to re-establish *C. vulgaris* as the dominant plant species on upland moorland. The second aim was to investigate factors that may limit *C. vulgaris* establishment on upland moorland post-wildfire by natural regeneration and from post-wildfire management. The main objectives of the research were to:-

i. Record vegetation cover and succession following post-wildfire management over the period of research.
ii. Investigate potential germination and growth of *C. vulgaris* seeds on bare peat to establish if physical or chemical properties of the peat inhibit *C. vulgaris* establishment.
iii. Determine moorland environmental conditions of bare peat and the potential of *C. vulgaris* seeds to germinate within these conditions.
iv. Record viability of *C. vulgaris* seeds under drought and controlled conditions within a laboratory.

v. Determine the potential use of a polyacrylamide gel to enhance environmental conditions as an aid to germination and growth of *C. vulgaris*.

vi. Investigate the dispersal properties of *C. vulgaris* seeds and their potential to recolonise bare moorland.

vii. Critically evaluate post-wildfire management of heather moorland and, from experimental results, propose more effective techniques and management options.

1.3 OUTLINE OF THESIS.

This thesis is organised into eight chapters, each of which is independent of the others; however each is a logical development upon the previous one. It is composed of a general introduction to upland moorland and background to research, followed by six experimental chapters and finally a general discussion. No literature review chapter is provided per se, as each experimental chapter contains its own.

An introduction to the study giving background information of the effects of wildfire, pre and post- wildfire management and ecology of upland heather moorland has been provided in this chapter. The aims of the thesis have also been presented. Chapter 2 provides details of the research sites; their history and management (pre and post-wildfire). Results of site surveys, maps and images of the condition of vegetation at each site at the start of research are presented. Chapter 3 considers methods of sampling and monitoring of vegetation within a moorland setting. These are investigated, discussed and evaluated. Results of trials by various methods are included.

Chapter 4 contains vegetation surveys, which show the change in species cover during the research period (2000 – 2005). Results from monitoring of permanent quadrats show succession in vegetation sub-communities and the effects of post-wildfire management on vegetation cover. Chapter 5 contains a controlled experiment with *C. vulgaris* seed to assess the effects of selected peat treatments on germination and growth. Chapter 6 investigates the viability of *C. vulgaris* seeds when exposed to drought conditions. Datalogger evidence shows the temperature and water content of bare peat within a moorland setting. The effects of using polyacrylamide gel to improve and maintain growth conditions for grass species are investigated. Chapter 7 investigates the potential of *C. vulgaris* seeds to spread and colonise a damaged site. Seed-traps were used to measure distance and quantity of seeds dispersal from parent plant. In chapter 8 the research aims are revisited and the implications of these results on moorland management post-wildfire are discussed. Experimental techniques are re-assessed and finally, ideas for further research are suggested.

2.0 CHAPTER 2

RESEARCH SITES.

2.1 *INTRODUCTION.*

Two upland heather moorland sites were selected for this research, one at Darwen Moor in Lancashire (Nat. Grid ref. SD678210) and another near Stalybridge in Tameside (Nat. Grid ref. SE005203) (Figure 2.0). Both sites were severely burnt by wildfire, albeit at different times (1980 and 1995 respectively) but received similar post-fire management.

Darwen Moor was selected for a number of reasons; its proximity to Preston and unrestricted access year-round, as no grouse shooting takes place, allowed monitoring on a regular basis. The Stalybridge site is occasionally closed for grouse shooting and was chosen specifically for its public inaccessibility, this gave protection to equipment when long-term monitoring was undertaken.

Most of the history and management information of the research sites given in this chapter is from personal communication with the Countryside Warden on Darwen Moor and the gamekeeper on the Stalybridge site. Also from personal experiences gained from working as a volunteer with Blackburn with Darwen Council's countryside services on Darwen Moor.

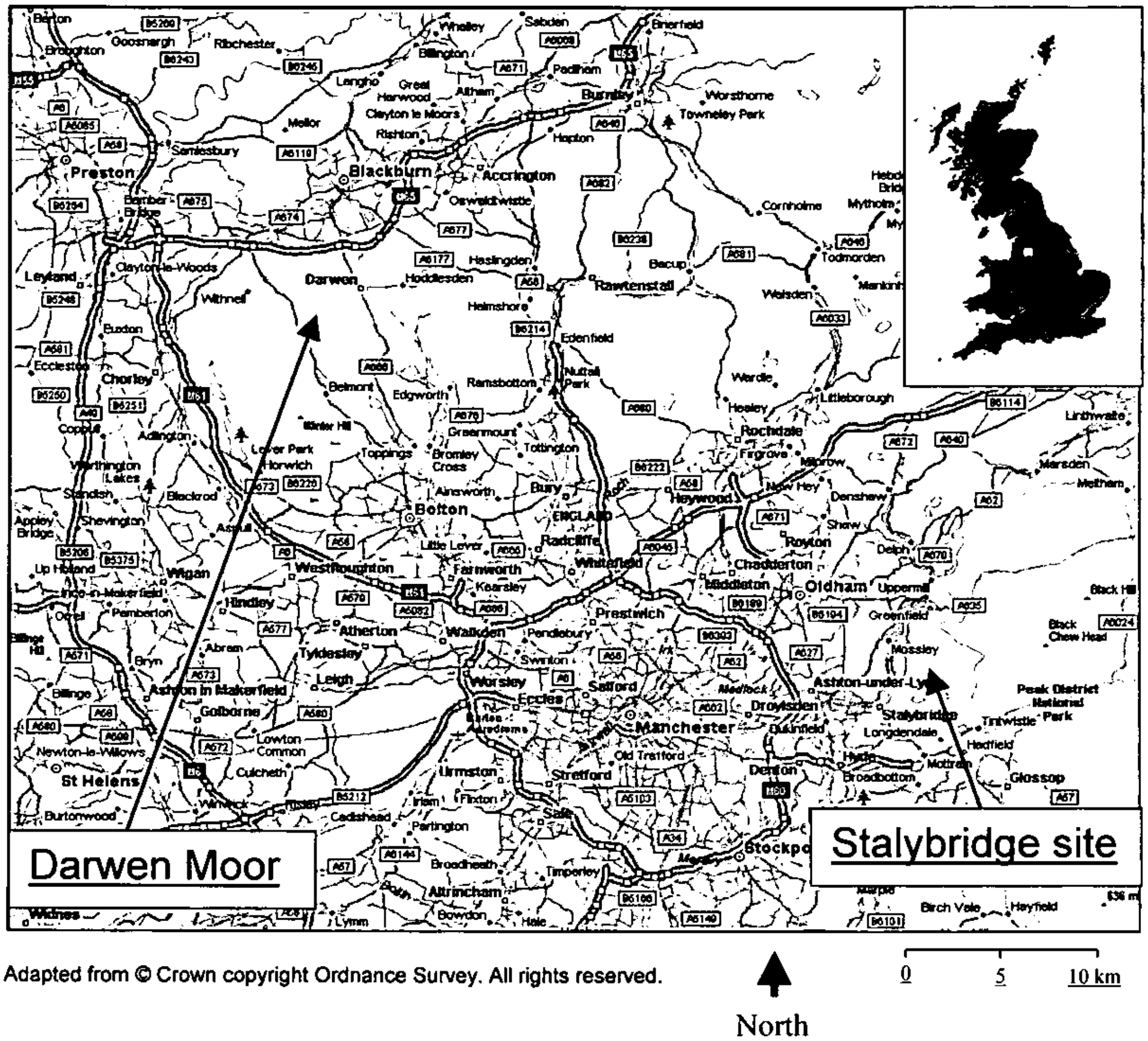


Figure 2.0 Position of Darwen Moor and Stalybridge research sites in the northwest of England.

2.2 *SITE SURVEYS.*

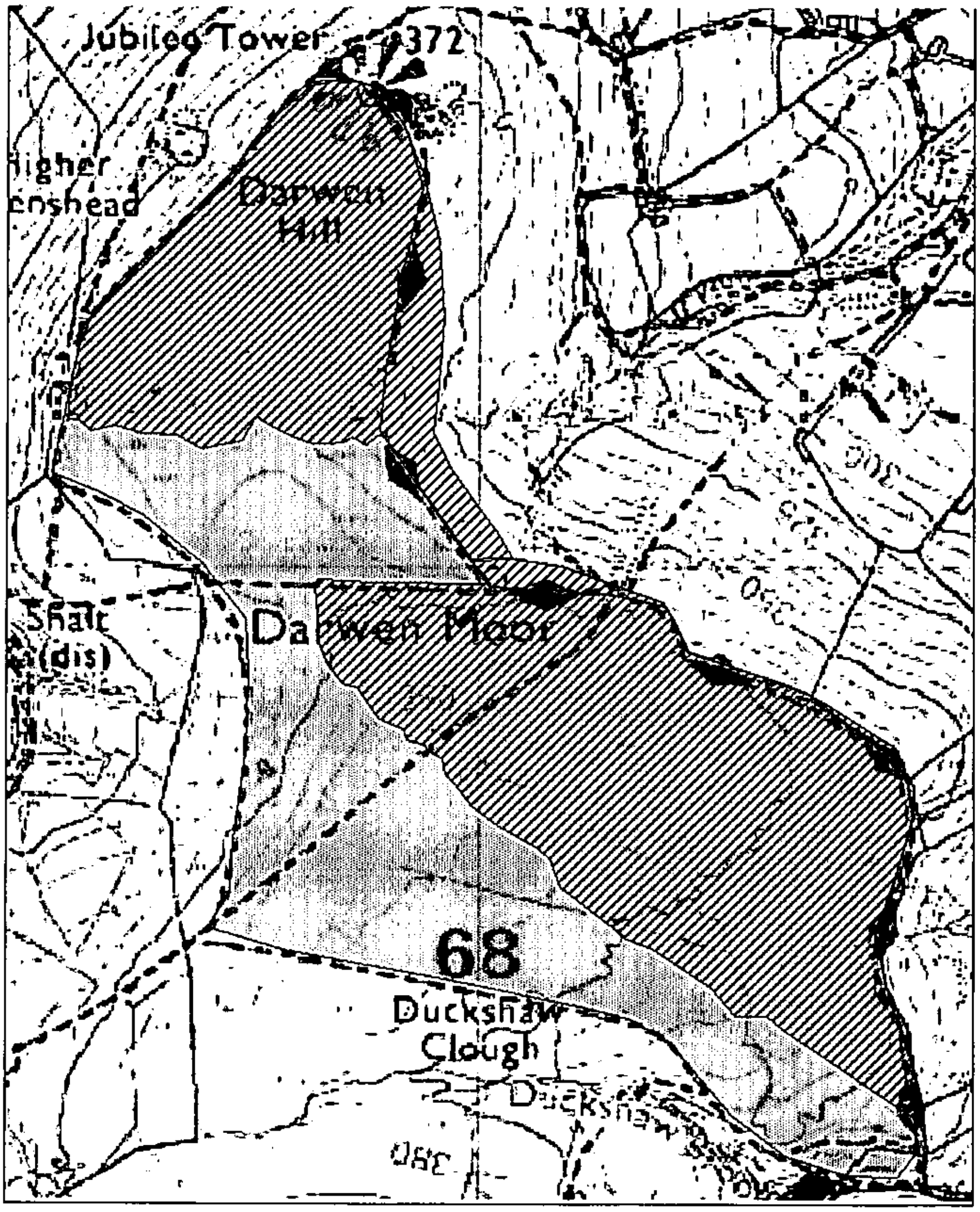
The plateau of Darwen Moor and the research site near Stalybridge were surveyed to measure the extent of the fires. Boundaries were walked (in 2000) and grid references recorded using a handheld Global Positioning System (GPS) (etrex, Garmin). Maps of sites were then produced using MapInfo a Geographic Information System (GIS) computer program (MapInfo Professional V5.5) (Figures 2.1 and 2.3).

2.3 *DARWEN MOOR*.

Darwen Moor overlooks the small town of Darwen in Lancashire and is owned and managed by the local authority, Blackburn with Darwen Council. It is part of the West Pennine Moors and designated as a Country Heritage Site and is 300-340m a.s.l. The organic soil lies on Millstone-grit (Geological Survey, Ordnance Survey map, 1971); there is also evidence of coal-mining on the moors with capped mineshafts and airshafts. The moor is surrounded on three sides by rough grazing pasture and joins Turton Moor to the south. A number of footpaths criss-cross the moor and local people use it extensively for recreational activities, such as walking, running and horse riding. The site had been managed as grouse moorland, although there was no active management of the heather just prior to 1995 and most of the heather was old and leggy (Dolimore 2000, per. comm.).

A vegetation survey completed by the Nature Conservancy Council (Now Natural England) in 1988 reported areas of the Moor had been subjected to previous wildfires. The percentage of heather cover of the whole moor is unknown from this survey, however, the plateau of the moor, was recorded as being heather-rich blanket bog, with many areas having a 90% cover of *C. vulgaris.*

Fires were started on the moor in August 1995, which destroyed much of the vegetation and burnt for many months in the underlying peat. Results from the site survey in 2000 showed that 40ha (of the 60ha research site) on the plateau of the moor were burnt in the 1995 wildfire. One small burnt area was not included in this study as proposed post-fire management was to plant trees, however this work had not been undertaken (as at June 2007) (Figure 2.1).



North

0 0.5km

Research site

Area of research site burnt in wildfire of 1995

Areas burnt but not included in research site due to proposed post-fire management.

Figure 2.1 Darwen Moor research site, map produced from grid references obtained in survey (2000) (Mapinfo computer program).

Immediately after the fire in 1995 and following advice from managers of The North Yorkshire Moors, post-fire management was undertaken (Dolimore, 2000 pers. comm). Money was obtained from a local charitable trust and remedial work was undertaken which consisted of liming, fertilising and seeding with grass species in the following percentages (application rates unknown): -

50% Sheeps Fescue – *Festuca ovina*
30% Chewings Fescue – *Festuca rubra,* sub-sp. *commutata*
20% Highland Bent – *Agrostis castellana*

Bales of cut heather were imported (origin unknown) and spread over Darwen Moor, by throwing armfuls into the air for the wind to spread the brash and seeds. The bales had also been stacked for many months before a volunteer force was organised to help spread the bales. Also with the assistance of local volunteers, including school children, potted heather plants (origin unknown) were planted out, however most were dead within a year (Dolimore 2000 pers. comm.). This work was concentrated on the flat plateau of the moor with full remedial work being hampered on the extreme southern section of the moor due to steep and uneven terrain being less favourable for tractor access (Dolimore 2000 pers. comm.).

Moorland management since the remedial work in 1995 and 1996 has been almost non-existent, except for small-scale muirburn management on the heather unaffected by the 1995 wildfire. This was undertaken by a gamekeeper from the adjacent Turton Moor to assist his own grouse numbers. Although rights of pasture for cattle and sheep exist, the area is not grazed. Figure 2.2 shows aspects of vegetation cover on burnt areas in 2000 (five years after the wildfire).

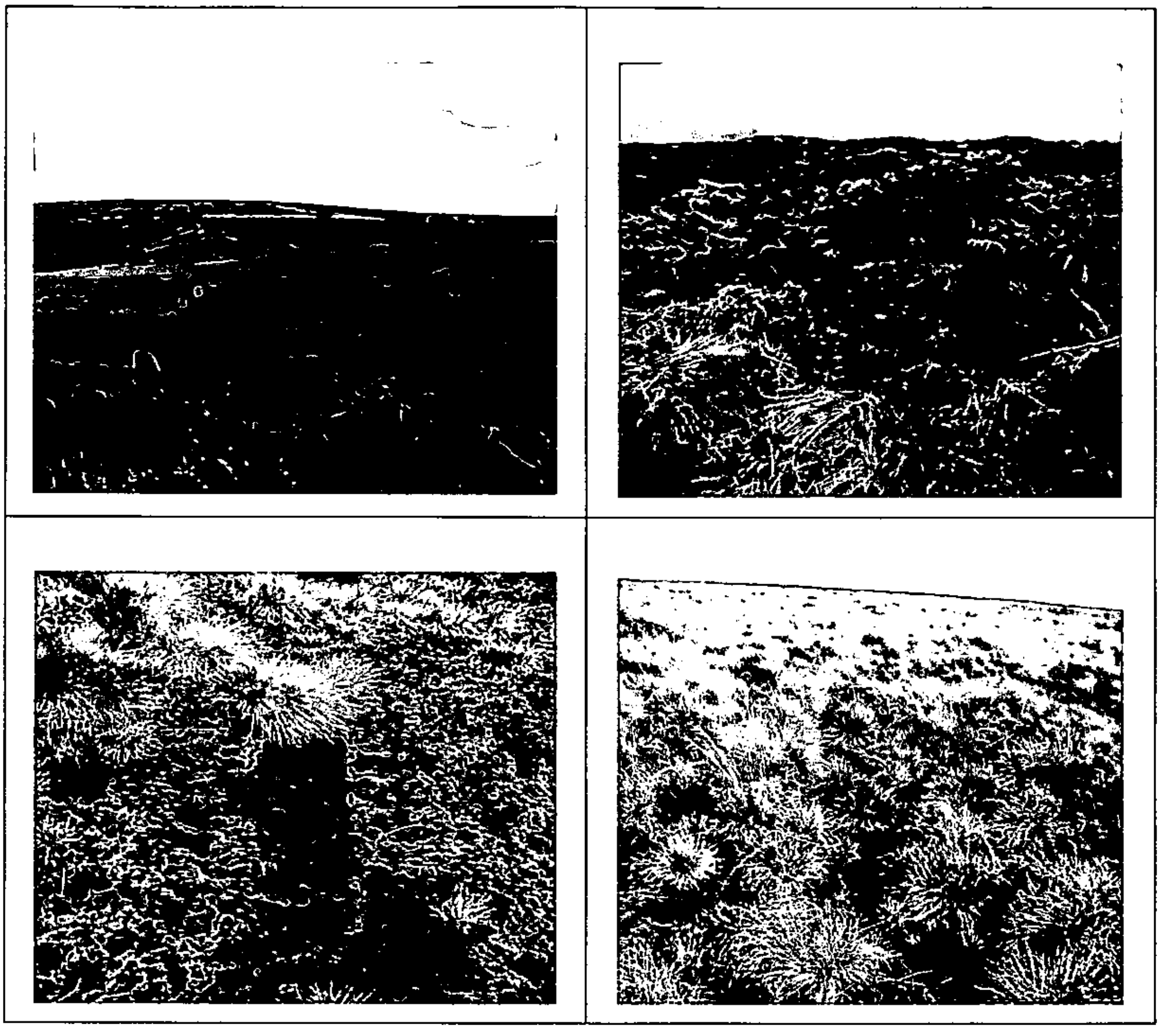


Figure 2.2 General images of Darwen Moor in 2000, five years after wildfire. Grass *spp.*, *Polytrichum spp.* and bare peat occupy large areas of the moor despite receiving post-fire heather management in 1995 and 1996.

2.3.1 Vegetation Surveys.

Results of vegetation surveys of Darwen Moor undertaken at outset and end of research period (2000 and 2005) are presented in Chapter 4.

2.3.2 Peat pH.

To obtain the pH of the bare peat ten samples were collected randomly. Using true random numbers (Random.com, 2000) a 'random walk' was undertaken. Sample points were located by taken a random number between 0 and 360, to give a compass bearing, followed by another random number (1-25) that indicates the number of paces that were taken in that direction. Peat samples (10g) were individually shaken for 2-3 minutes in

50ml of distilled water (1:5 ratio) and left to settle for two minutes. Suspensions were measured using a Sentron pH meter. A mean pH of 3.8 was recorded (range 3.61 to 4.0, median 3.79).

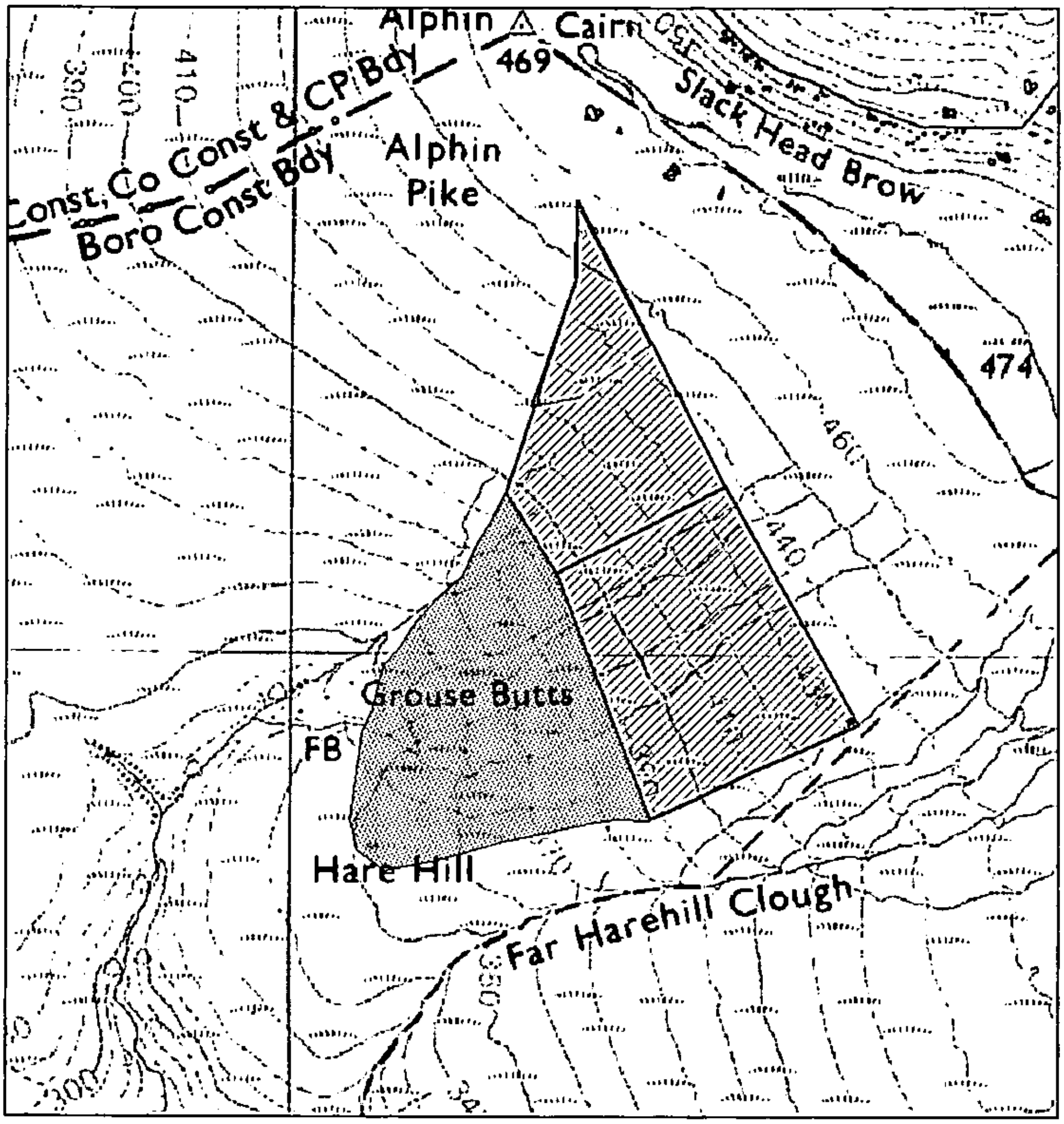
2.4 *STALYBRIDGE RESEARCH SITE.*

This site (16ha) overlooks the village of Carrbrook, northeast of Stalybridge, Tameside and is 380 – 460m a.s.l. The organic soil lies on Millstone-grit (Geological Survey, Ordnance Survey map, 1971). The site is part of privately owned heather moorland (Enville and Stalybridge Estates), managed for grouse shooting by a gamekeeper with no access to the general public. Management of surrounding heather is by muirburn with a mosaic of different aged *C. vulgaris* (section 1.1.3).

Following a severe wildfire in 1980, that completely destroyed all vegetation within the 16ha research site, post-fire management was to lime, fertilise and seed with grass (species and application rate unrecorded). Grass germinated successfully and grew for a short period, but died within weeks (Kelly 2000, pers. comm.). Bales of cut heather were also spread to act as a supply of *C. vulgaris* seeds. The site is within an Environmental Sensitive Area (ESA) and is fenced to keep sheep out; however, subsequent peat erosion has left ample room for sheep to gain access beneath the fence. The fence encloses most of the burnt area but much degraded moorland, from post-fire erosion and peat deposition, remains outside of its protection. Although there is a dividing fence (reason unknown) the whole fenced area is classified as the research site for this study (Figure 2.3).

Deep gullies run through the site, eroded by water from overland flow, which has exposed the large stones and mineral soil of the underlying bed-rock of Millstone-grit. Figure 2.4 shows the extent of vegetation regeneration twenty years after the wildfire of 1980.

A further wildfire (April 2003) removed most of the *C. vulgaris* on the moor in which the fenced area is located and burnt the regenerated vegetation in the northern section of the research site. However, the surface peat and seed-bank remained intact and regrowth of *C. vulgaris* on the moor outside the fenced research site occurred within weeks (Kelly 2003 pers. comm.). Some regrowth of the burnt *C. vulgaris* plants within the fenced research was observed.



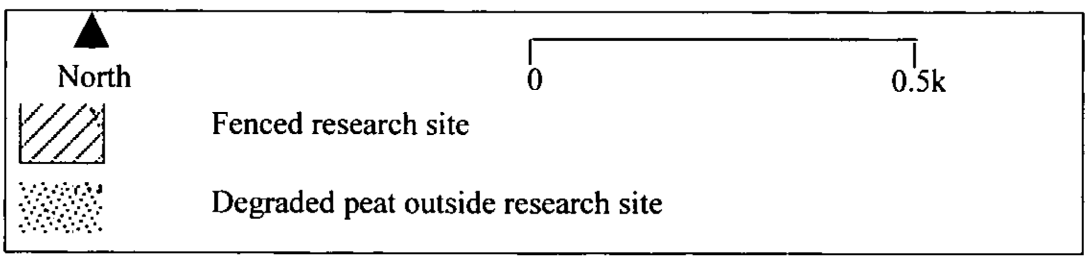


Figure 2.3 Stalybridge site, map produced (MapInfo computer program) from grid references obtained in survey (2000).

Figure 2.4 General images of the Stalybridge research site in 2000, 20 years after the wildfire and post-fire management. Large stone-filled gullies run through the site, where water has removed the peat. Areas of bare peat, with a hard crust, lie between the gullies. Most of the regenerated vegetation (grass *spp* and *C. vulgaris*) is confined to the mineral areas where peat has been eroded.

2.4.1 Vegetation Surveys.

Results of vegetation surveys of the Stalybridge Research site undertaken at the outset and end of the research period (2000 and 2004 respectively). In 2000 69% of the cover of this site was bare peat, full results are presented in Appendix 1.

2.4.2 Peat pH.

Ten samples were collected and analysed as in section 2.3.2. A mean pH of 3.7 (range 3.55 – 3.9, median 3.68) was recorded.

3.0 CHAPTER 3

EVALUATING VEGETATION SAMPLING METHODS FOR USE IN LONG TERM MOINITORING ON HEATHER MOORLAND POST-WILDFIRE.

3.1 *BACKGROUND TO THIS STUDY.*

Habitat management, whether for a given species or to maintain a desired community, may rely on knowledge of plant species present, abundance and composition of the plant community and their changes over-time. Data of plant community can assist in assessing the success of management, for example evaluating vegetation recovery on footpaths closed to reduce outdoor recreation activities in woodland (Roovers *et al.* 2005).

Detailed field surveys are often used to acquire information of vegetation communities. However, one of the main issues associated with field techniques in surveys is how to increase the accuracy of estimating vegetation cover (Kent and Coker 1992). Although harvesting the biomass of above ground vegetation will give an exact measurement of above ground plant abundance, this method cannot be used when damage to the surveyed site is undesirable, therefore a non-destructive method is required. The accuracy of field measurements may be influenced by many factors; for example, different observers and methods used (Nilsson and Nilsson 1985, Fenner 1997). Reproduction of consistent results has also been shown to be difficult (Hope-Simpson 1940) with few examples of quality control cited in the literature (Kercher *et al.* 2003).

Traditionally, one of the most frequently used methods of estimating vegetation cover is the point quadrat or 'pin-frame', which is one of the most objective ways to sample vegetation cover, (Bonhamn 1989, Silvertown *et al.* 1992). This method uses a frame that supports a row of vertical rods above the vegetation, when the rods are lowered, the number of 'hits' a species receives is recorded and the vegetation cover calculated. Recording every hit of the pointer (multiply hits) as it is lowered will give total cover. Single hits of the pointer on each individual plant will give relative numbers of each species, first hit on each species will give proportional or percentage cover, and top canopy cover is when only the first hit is recorded (Chalmers and Parker 1989). Size of rod has been shown to influence results with an over exaggeration of the cover estimate when a large diameter pin is used (Goodall 1951). As this method is objective it may not be so susceptible to operator influence as other methods, however, it is very time intensive (Fenner 1997). A visual estimate of cover where a frame or grid quadrat is placed over the plant species and cover estimated is also assumed to be accurate (Fenner 1997). However, this method is subjective and may therefore be influenced by the surveyor, size of grid used and the vegetation surveyed (Goodall 1951, Shimwell 1971, Fenner 1997).

Aerial photography is accepted as a method for recording vegetation change (on a large scale) and has been extensively used, for example Zharikov *et al.* (2005), Tong *et al.* (2006), Booth *et al.* (2007). Photography of quadrats has also been used to record changes in vegetation cover; however, early works with this method (Cooper 1924, Owens *et al.,* 1985) were not supportive of its use, although Law (1981) used a photographic technique to follow the lives of individual plants. With the advance of digital photography and computer technology, more trials and use of photography within vegetation surveying have been undertaken. Bennett *et al.,* (2000) concluded that vertical photography and digital image analysis was sufficiently accurate in a study for measuring cover change in perennial grasslands. Vanha-Majamaa *et al.* (2000) used computer software to distinguish between the covers of different plant species from digital images. However, results from these computer-analysed images showed this method was unreliable in estimating cover of multi-layered vegetation but was useful in detecting changes in vegetation with a simple vertical structure.

Determination of digital photography accuracy for surveying over more traditional methods has always been problematic. Dietz and Steinlein (1996) maintain that accuracy of 1 – 2% is possible with photography when compared to a point quadrat depending on the dominance of the plant species being analysed. Whilst Foster *et al.,* (1991) maintain that photographic surveys underestimate cover of sessile marine organisms, when compared to point quadrat survey, particularly when the assemblage was layered.

Digital photography has also been used to estimate above ground biomass. Smith *et al.*, (2000) demonstrated this in monospecific macrophyte stands, where results showed there was no significant difference between the photographic and dry weight data.

The main difficulty of evaluating different sampling methods to estimate vegetation cover is that the real cover value is unknown. Fenner (1997) overcame the problem of this unknown factor when he used a practical class of undergraduates to show that the commonly used methods of estimating vegetation cover differed greatly in their accuracy. Using a photograph of a simulated grassland turf, where the real cover was known, the students estimated the cover using different methods (quadrats with different grids and point quadrat). Fenner's (1997) study showed that shapes and sizes of vegetation influenced accuracy with compact shapes and small areas easier to estimate than dispersed shapes and large areas. Results suggested that a quadrat with a 4 x 4 grid (quadrat divided into 16 even squares) was the most accurate. The point quadrat method of estimating vegetation cover was shown to be the most inaccurate. One criticism of Fenner's study was that a large number of students were used which may increase estimating error, however, this was acknowledged by Fenner (1997) and a coefficient of variation was included in the estimates. Another study using a known 'vegetation' was undertaken by Lindquist (1932) who used cut paper to demonstrate over-estimation of percentage cover by large diameter pins in point-quadrat assessments.

3.2 RESEARCH AIMS.

The principal aim of this chapter was to investigate a method of vegetation sampling that would be suitable for use on upland moorland. The method had to be reliable, efficient and relatively rapid as adverse weather conditions often limit the number of hours that can be spent on moorland in early spring and late autumn. Accuracy also had to be assured throughout the surveying period, as monitoring was to proceed for the whole of this research. The method selected was used in full site vegetation surveys and with permanent quadrats.

3.3 *MATERIALS AND METHODS.*

Two methods of vegetation sampling were evaluated to assess their potential use in an upland moorland environment. A frame or grid quadrat with images captured by digital photography was compared to a point-quadrat. Two studies were undertaken, the first with a known survey area and simulated 'vegetation' cover and the second in the field on an upland moorland site.

3.3.1 Evaluation of digital photography with a known simulated 'vegetation' cover.

An area (3m x 2m) was prepared with simulated 'vegetation' with a known percentage cover using varying sized pieces of paper in four colours. The paper 'vegetation' was randomly scattered on a level survey area but the individual pieces did not overlap. This simulated four different 'vegetation types' with the uncovered survey area representing 'bare soil' or unvegetated area. The sizes of 'vegetation' ranged from $100cm^2$ to $625cm^2$ and were comprised of random shapes with 65% 'un-vegetated'. The percentage cover of the 'vegetation' was not calculated until after the survey so as not to influence the estimation of cover. As the coloured paper did not overlap, total cover was 100%. This method was similar to that used by Lindquist (1932) and Fenner (1997). A quadrat ($0.25m^2$) placed randomly; (using coordinates derived from true random numbers) was used throughout this investigation. Size of quadrat was selected to fit the camera viewfinder at a height of approximately 1m.

An image of each quadrat was taken with a digital camera (Sony MVC-FD83, image size 1216 x 912 pixels with images saved on a floppy-disk); the images were transferred to a computer. The experiment consisted of ten samples, replicated three times (n=30). Simulated 'vegetation' was rearranged between each sample batch.

3.3.1.1 Correction of picture warp.

The problem of picture warp, where the angle of the photographed terrain or the angle of the camera shows the square quadrat to have uneven sides, as in figure 3.0, was corrected prior to calculation of 'vegetation' cover.

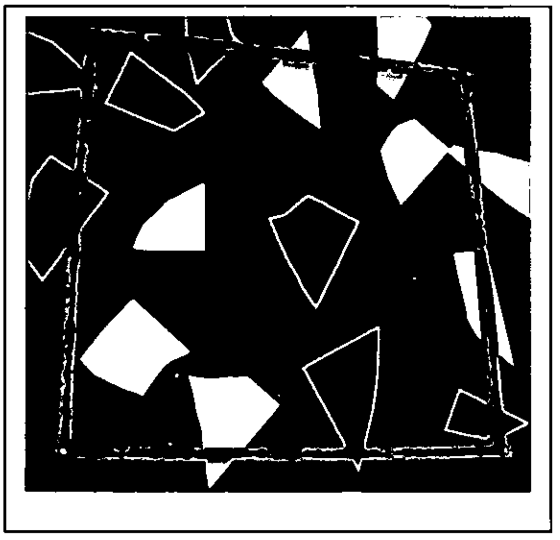


Figure 3.0 Image of simulated 'vegetation' within square quadrat, sides appear to be uneven due to angle of quadrat on rough terrain or camera angle.

Picture-warp can be removed and the true shape of the image restored. Geometric correction or rubbersheet transformation (Baxes, 1994) of the distorted pictures was performed using Adobe-Photoshop (Adobe Systems Incorporated, 2000) by using the 'crop' tool with the 'perspective' option selected. Figure 3.1 shows the corrected picture image of Figure 3.0. (Further details are given in Appendix 2).

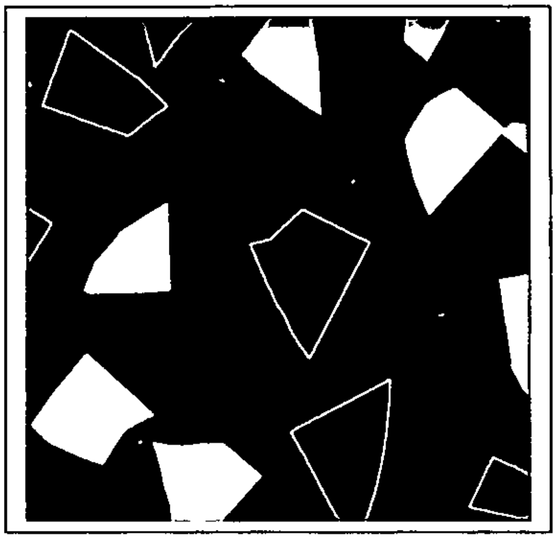


Figure 3.1. Image of simulated 'vegetation', as in figure 3.0, but 'squared' maintaining the perspective and cropped to remove area outside quadrat. Image is ready for superimposition with a grid and vegetation cover calculation.

Using Adobe-Photoshop the images on the computer screen were superimposed with a grid (5 x 5) and a visual estimate of the percentage cover made and results recorded, (Figure 3.2).

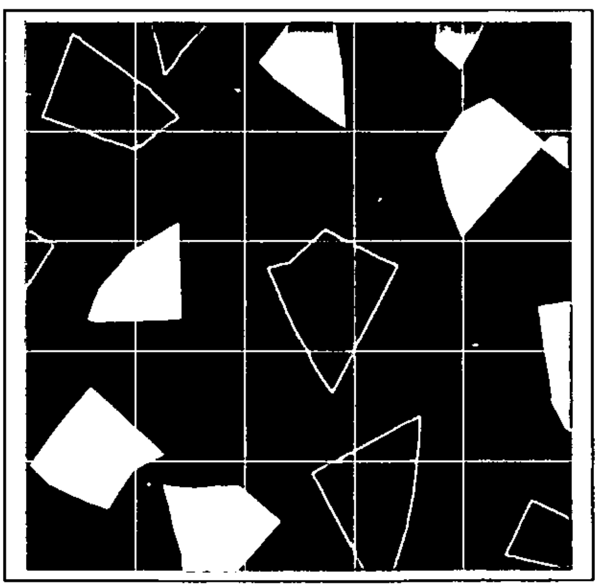


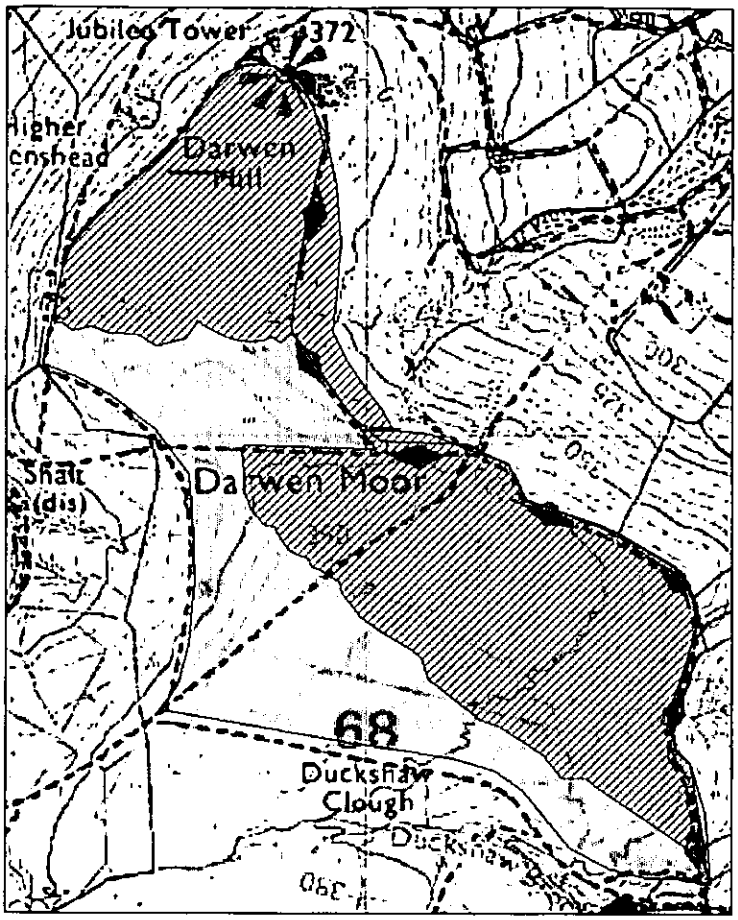
Figure 3.2 Image of sample site superimposed with grid ready for estimating by 'eye'.

3.3.2 Evaluation of point-quadrat with a known simulated 'vegetation' cover.

A quadrat ($0.25m^2$) was placed on the randomly selected sample sites, and 'vegetation' sampled with 25 pins (equivalent to 100 points/m^2). The experiment consisted of ten samples per replicate with 3 replicates (n=30). Position of each pin (2mm diameter) was determined by dividing the quadrat into a 36 square grid, a pin was placed at each cross-line. The first 'vegetation' or 'bare soil' to received a 'hit' or touch from a pin was recorded. The percentage of 'vegetation' cover within the quadrat was then calculated.

3.3.3 Evaluation of point quadrat and digital photography surveying methods in the field.

A quadrat ($0.25m^2$) was placed every 5m along a transect on the burnt section of Darwen Moor (n=25) figure 3.3. Each quadrat was assessed by the two methods, point quadrat with 25 points and digital photography. Vegetation cover for the point-quadrat survey was calculated as in section 3.3.2. Digital photographs were manipulated within Adobe-photoshop and vegetation cover calculated as section 3.3.1.1, an example of corrected image of moorland vegetation is presented in Figure 3.4.



NORTH

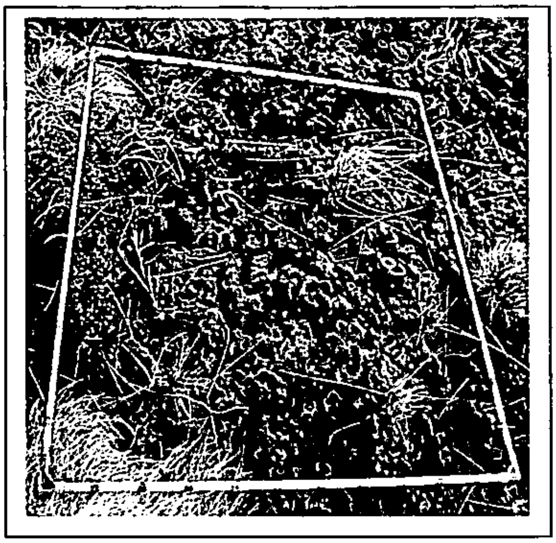
0 0.5k

Research site

Area of research site burnt in wildfire of 1995

Areas burnt but not included in research site due to proposed post-fire management.

Figure 3.3 Transect line (red line) for the assessment of vegetation cover by point quadrat and digital photography, (25 samples).



a)

b)

Figure 3.4 Example of sample site showing uncorrected (a) and corrected image (b), prepared for superimposition of grid and estimation of vegetation cover.

3.3.4 Statistical analysis.

Data were checked for homogeneity of variance using Levene's test. An ANOVA was performed using the SPSS statistical package (Version 13.0) to test differences between:-

i. Results of two sampling methods (point quadrat and image capture by digital camera) and between sampling methods and a known simulated 'vegetation' cover.

ii. Results of two sampling methods (point quadrat and image capture by digital camera) recorded on upland moorland.

3.4 Results.

3.4.1 Vegetation sampling with known cover.

Levene's test showed homogeneous variance ($P > 0.05$). The results of the ANOVA show there was no significant difference in vegetation cover within the quadrats using point quadrat or digital photography ($P > 0.05$). Also no difference was recorded between the methods and the actual 'vegetation' cover ($P > 0.05$). Results are given in figure 3.5.

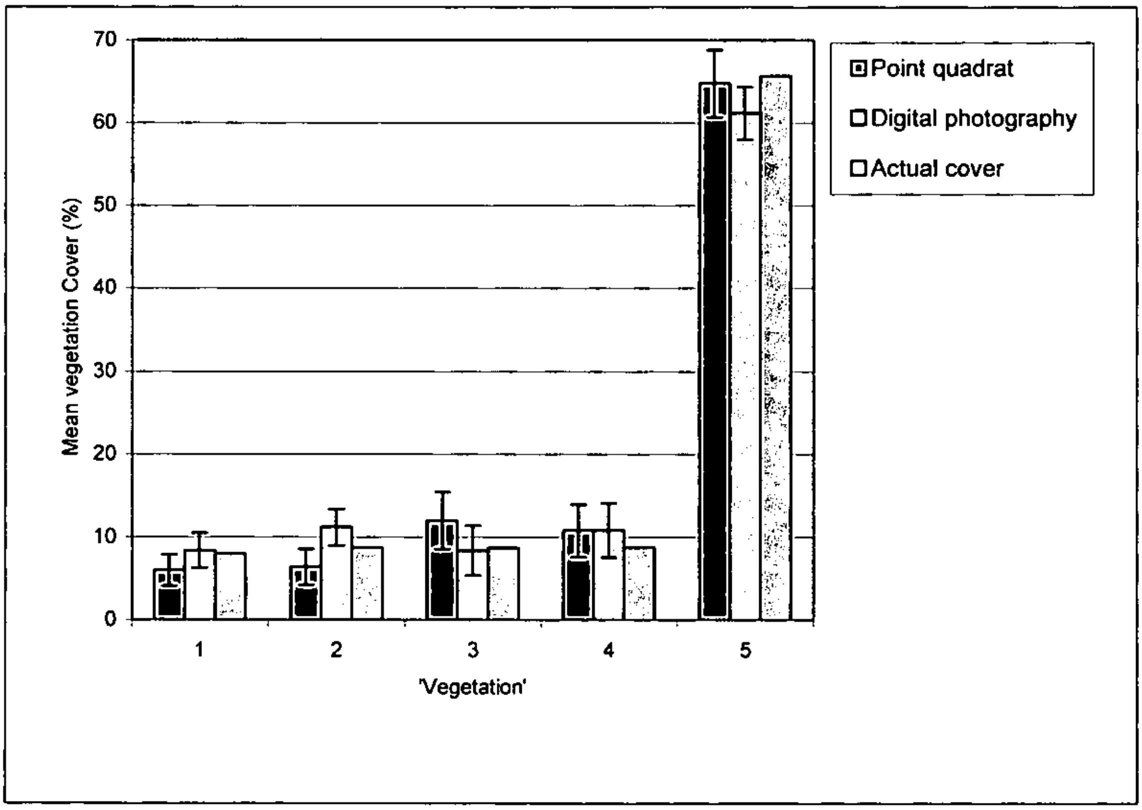


Figure 3.5 Estimated cover of artificial 'vegetation' using point quadrat and digital photography, in addition to actual cover. Numbers 1-4 represent simulated vegetation, and 5 bare soil or background vegetation. (Data mean ± SE).

3.4.2 Vegetation survey to evaluate field sampling methods.

The results of the ANOVA show there was no significant difference in vegetation cover between the two methods tested (point quadrat and digital photography) (P>0.05). Results are shown in Figure 3.6.

The largest difference in cover between the two survey methods were recorded in the moss species (other than *Sphagnum spp.*) and bare peat, 4.5% and 6.2% respectively, however these were not significantly different.

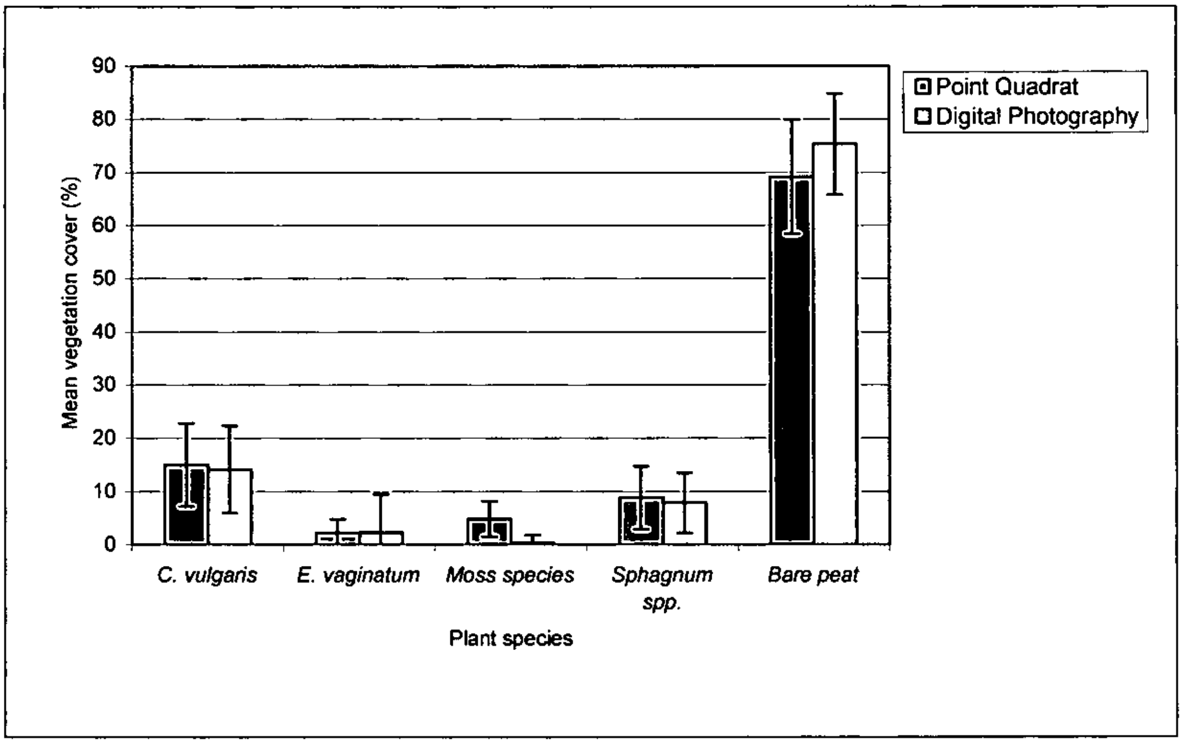


Figure 3.6 Vegetation cover results from quadrats along a transect on the burnt section of Darwen Moor, survey by point quadrat and digital photography (Data mean ± SE).

3.5 *DISCUSSION.*

Two methods were evaluated for use on upland moorland to sample the vegetation cover throughout this research, i) point quadrat, a traditionally and frequently used method and ii) a combination of frame quadrat with the data captured by digital photography and the image manipulated on a computer and cover visual estimation. Selecting a method that was accurate and consistent throughout the surveying period was important and using a known cover allowed comparisons to be made. The results of both methods suggest they are not significantly different ($P > 0.05$) when compared to a known cover.

One aspect of vegetation properties, which was not incorporated into these investigations using an artificial vegetation cover or into Fenner's (1997) study, was the height of vegetation. However, studies on vegetation height show accuracy to be more consistent on low shrub than on tall vegetation (Vanha-Majamaa *et al.* 2000), as was the case with the artificial 'vegetation' and the vegetation on the moorland.

Although results from the investigation on Darwen Moor could not be analysed against a known vegetation cover, the results showed there to be no significant difference ($P > 0.05$) between the two sampling methods used.

Fenner (1997) suggested the most accurate grid quadrat for estimating vegetation cover by visual estimating was a 4 x 4 grid. However, in these investigations all photographic data was analysed by a 5 x 5 grid, this grid with 25 small squares was superimposed on the image of the quadrat on a computer screen and was shown to be the simplest and most rapid to use.

There was a problem of picture-warp with the digital photographs, but this was corrected within Abode-Photoshop. This image manipulation negates the need to have the camera parallel with the ground or the need to spend time erecting and levelling a camera tripod.

The advantages of using digital photography over conventional methods in the estimation of vegetation cover are discussed by Smith *et al.* (2000), who also suggest that fieldwork time is reduced. Enhanced speed of data collection is most useful in areas of poor climatic conditions or poor accessibility, as in this research. As the time per sample is reduced the potential to take more samples is achieved, thus ensuring sufficient comparable data is collected. With reduced time in the field sampling fatigue does not influence results; time spent analysing the photographs on the computer can be interrupted with rests within a safe environment.

The images from a study of vegetation coverage obtained by digital photography can be easily archived, allowing data re-examination or for use in retrospective studies that may examine new questions (Smith *et al.* 2000). This is in contrast to other methods where the primary data is lost once the quadrat is removed, leaving only the collected data.

Goodall (1951) suggested that the smaller the diameter of a pin used in pin-frame, the more accurate the vegetation estimate would be. In this evaluation study it was decided to use 2mm diameter pins as only the first plant species or bare peat to be 'hit' or touched by the pin was to be recorded. These pins also proved robust enough to be carried onto the moor and did not bend in operation.

Accuracy and speed were the main criteria by which the two survey methods were evaluated. Digital photography has shown to be as accurate as, or better than, the traditional point quadrat, a method that is widely accepted as a method of vegetation estimation. All this is in agreement with other academic work (Dietz and Steinlein 1996, Bennett *et al.* 2000, Smith *et al.* 2000), which suggests that photography and digital image analysis is an acceptable and accurate method of vegetation sampling.

Counting the different coloured pixels within a digital image and then calculating the percentage in relation to the total pixels count is possible (Adobe-photoshop, Schooler and McEvoy 2006, Riegl *et al.* 2005). However, in this investigation, this method of image analysis was not used due to the difficulty in distinguishing individual species of plants by their colour. Nevertheless, this method was used in a later experiment (Chapter 6) to analyse the vegetation cover of grass species within a bare peat section of the Stalybridge research site.

From the results of these experiments and support from other literature it was accepted that vegetation sampling on both research sites would be conducted by use of digital photography, with images displayed on a computer and vegetation cover calculated by eye. This method proved to save time in the field and has been shown as accurate as a more traditionally survey method. However, to extend the method evaluation, one study of vegetation sampling on Darwen Moor was conducted using both photographic and point quadrat (Chapter 4).

4.0 CHAPTER 4

CALLUNA VULGARIS REGENERATION ON UPLAND MOORLAND POST-WILDFIRE AND REMEDIAL MANAGEMENT.

4.1 *BACKGROUND TO THIS STUDY.*

In regenerative moorland management post wildfire the use of nurse plants is a well-recognised but often varied procedure (Tallis and Yalden 1983, Putwain and Rae 1988, Anderson *et al.* 1997). This study investigates if this post-wildfire management inhibits or facilitates the re-establishment of *C. vulgaris,* also do the nurse species from the post-wildfire persist or disappear over time? All investigates were conducted on Darwen Moor five and ten years after the wildfire of 1995 (Section 2.3).

4.1.1 Natural regeneration post-wildfire.

Research on severely burnt moorland shows that vegetation recovery is slow through natural regeneration (Maltby *et al.* 1990, Roze 1993); this is illustrated on the North Yorkshire Moors where eight years after a severe burn a bryophyte-dominated vegetation was present with 2% cover of *C. vulgaris* and 30% of the moor remaining unvegetated (Maltby *et al.* 1990).

Where an ash surface remains after a severe fire, lichen and algae have been shown to form a film over the surface within the first year (Maltby *et al.* 1990). Legg *et al.* (1992) and Hobbs (1985) suggest these lichen-algal crusts may inhibit *C. vulgaris* establishment. Bryophytes have been shown to become the dominant vegetation up to three years after a fire (Maltby *et al.* 1990), but some have been reported to have a positive association with *C. vulgaris* seedlings (Gimingham 1972, Bridges 1985, Equihua and Usher 1993). Between three and ten years after a fire, *Polytrichum spp* are reported to form large beds, which often exclude other species (Maltby *et al.* 1990, Legg *et al.* 1992). After ten years, grass species are recorded and may become dominant (Clement and Touffet 1990, Roze 1993,) preventing establishment of other vascular species including *C. vulgaris* (Clement and Touffet 1990).

Many models attempt to explain succession or the temporal changes in the structure and species composition of vegetation. Most notable is that of Clements (1916) who described the developmental stages through which vegetation passes until it reached a state of equilibrium with the climate and major geological factors of the area. However, there are many criticisms of the generality of the mechanisms of succession that lead to a climax vegetation as described by Clements (1916).

Connell and Slatyer (1977) suggested three models and associated mechanisms of successional change:- facilitation, inhibition and tolerance, which describe plant species interactions during succession. In the facilitation model, species replacement is assisted by environmental changes which make it less suitable for new recruitment of early successional species but more suitable for late successional species. This model is similar to Clements (1916) and culminates in a stabilised community when it reaches a climax and is in equilibrium with its environment. Succession is prevented in the inhibition model by the current species of the site, with succession only progressing when the initial species are damaged or killed. In the tolerance model, the initial colonisers have little or no effect on later species, which establish and grow to maturity in the presence of others either utilising an alternative 'niche' or a lower resource level; in time the early colonisers are replaced with species more tolerant to limiting resources. Connell and Slatyer (1977) suggest that in severe environments the facilitation model best fits succession. However, these models are not mutually exclusive and most successional sequences may involve a mixture of models or a change in different stages of succession.

Grime (1979) and Tilman (1988) both give plant strategy theories to try to understand the distribution, interaction with the environment and the assembly of plant communities. However, these have been critically reviewed by Craine (2005) and debated by Craine (2007), Grime (2007) and Tilman (2007). The role of nurse plants, as used in post-wildfire moorland management, may also have an effect on successional changes (Temperton and Zirr 2004).

4.1.2 Re-vegetation from regenerative moorland management.

There are very few examples in literature that show vegetation re-establishment post-wildfire management. One example is the long-term effects (20-45 years) following management by fertilising and seeding with a nurse species on damaged sited in Iceland. Here, a significant increase in plant cover (7-100%), when compared to untreated plots, was reported (Gretarsdottir *et al.* 2004). These degraded sites in Iceland have many of the characteristics and the same problems as upland moorland in the UK. These include highly unstable surfaces from wind abrasion, erosion and frost-heave (Magnusson 1997).

Other management techniques using *C. vulgaris* seeds have been used in many restoration projects. These include using harvested heather shoots that contain seeds within the capsules, application of *C. vulgaris* seeds and capsules, or cleaned seeds (for examples see Putwain and Rae 1988, Pywell *et al.* 1996, Anderson *et al.* 1997 Anderson 2004), Restoration projects, which have received such management, include *C. vulgaris* reinstatement after eradication of *M. caerulea*, (Anderson 2004) and establishment of *C. vulgaris* into farmland (Pywell *et al.* 1994).

4.1.3 Methods of vegetation classification and description

To provide a method of description and cataloguing plant communities in Britain the National Vegetation Classification (NVC) was commissioned in 1975 by the Nature Conservancy Council (NCC). British Plant Communities (Rodwell 1991a & b, 1992, 1995, 2000) a five-volume set of books was the published account of the NVC. Each volume concentrates on one major type of environment, for example Mires and heaths (Rodwell 1991), and gives the plant classification and community descriptions associated with that environment. The NVC, whilst essentially reliable, is not meant as a static edifice, but as a working tool for the description, assessment and study of vegetation (Rodwell, 2006). There are some deficiencies in the coverage and much unexplained variation in the classifications (Rodwell, 2006). One of these 'deficiencies' is that *Polytrichum commune*, which forms large patches on acid grasslands and mires is not described by the NVC as this vegetation cover is seen as a result of poor management, i.e. over grazing (Averis *et al.* 2004).

TABLEFIT version 1.0 (Hill 1996) is a computer program used to identify vegetation types described in the NVC. From a list of species, together with their frequency and abundance, the program will assign a vegetation type. The program gives a list of five-plant communities and their goodness-of-fit; the correct community is usually in this list (Hill 1996). If this goodness-of-fit is very poor (<50%) then the NVC types should not be assigned to the sample.

Plant community data are multivariate in nature and there are many other methods of classification of plant communities. Two-way indicator species analysis (TWINSPAN) is a computer program that analyses samples of vegetation cover. TWINSPAN divides samples into groups of similar vegetation cover but does not place the divisions between the vegetation types in the same place as the division in the NVC and the end groups may be different. However, it is possible to use percentage cover of bare peat and *Polytrichum spp.* in TWINSPAN analysis.

4.2 *CHAPTER AIMS.*

The aims of this chapter were to evaluate the effectiveness of post-fire remedial management of liming, fertilising and seeding with nurse species for the restoration of severely burnt moorland; with the effectiveness of post-wildfire management measured by the regeneration of *C. vulgaris* on the burnt section of moor. Also, to determine if peat depth had any influence on colonising plant species.

Two investigations are presented in this chapter. The first was a full survey of Darwen Moor at the start and end of the research period, which also incorporates a peat depth plant association study (section 4.4). The second investigation used data from the first full survey of the moor to identify areas for the placement of permanent quadrats; these permanent quadrats were monitored for four years (section 4.6).

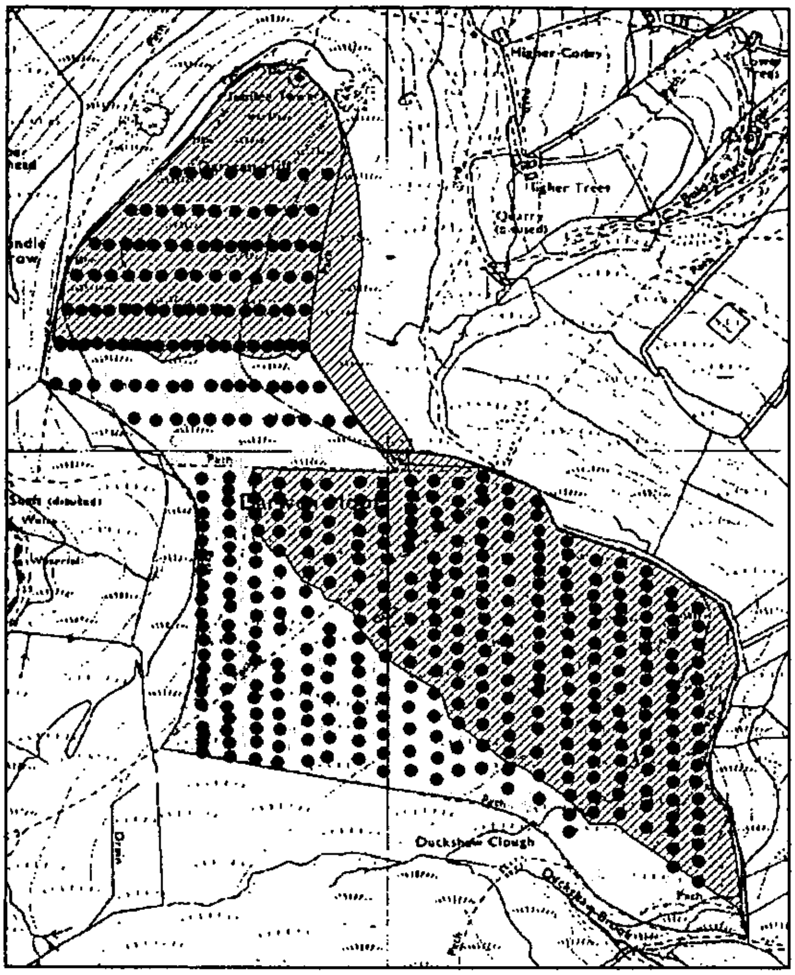
4.3 *DARWEN MOOR GROUND COVER SURVEYS.*

4.3.1 Materials and methods.

Two surveys were undertaken on Darwen Moor, the first in the autumn of 2000 and the second in 2005. The whole plateau of Darwen Moor was surveyed including the area burnt in the wildfire and the unburnt area (section 2.3), some of which had been subjected to muirburn management since the 1995 wildfire.

Twenty-eight parallel transects were established across the moor separated by approximately 25m with 456 quadrats ($0.25m^2$) placed at intervals of approximately 25m along these transects. Transect lines were followed using a compass bearing and/or the 'go to' function of a handheld Global Positioning System (GPS) (Garmin etrex) for directions to a grid reference. Transect lines in both surveys utilised the same grid references, with the same number of quadrats, however, sample sites were not marked and therefore, it must be assumed that quadrats were not placed in exactly the same locations (Figure 4.0).

Surveys were undertaken after the 12^{th} August (start of grouse shooting season) and when selected environmental conditions were met: night-time temperature < 10°C for 5 consecutive nights (using max/min thermometer, 1m above ground) at Grid Ref: SD671288 and the first fall of *Acer pseudoplatanus* (sycamore) leaves at Grid Ref: SD674211. This ensured that no birds were disturbed and monitoring was carried out at approximately the same period of vegetation die-back. Surveys were all completed within fourteen days.



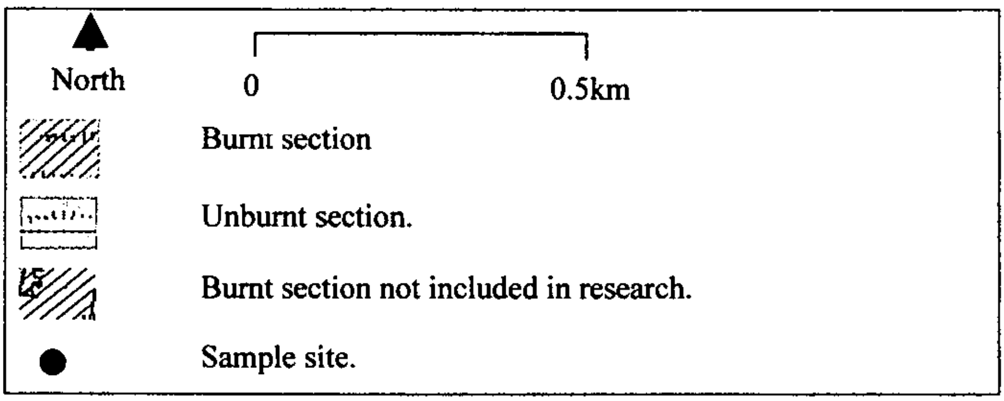


Figure 4.0 Darwen Moor sample sites for surveys (2000 and 2005).

Evaluation of the quadrats was conducted using digital photography (section 3.2), with images captured on floppy disks. Field notes were also taken to record any unusual vegetation species or composition of the sample, for example *C. vulgaris* being burnt by muirburn or presence of a non-moorland plant. Images were transferred and percentage cover calculated using a computer with Adobe-photoshop as described in section 3.3.

During the 2005 survey, although conducted at the same time of year as the 2000 survey, classification of grass species became problematic due to a lack of flower heads that aided identification. There was also a problem identifying *E. vaginatum* (harestail cotton grass) as it grew very closely and interwoven with grass species. Therefore, for comparative purposes, all data from the first survey were re-analysed, along with the data from the second survey, with all grass species and *E. vaginatum* classified as 'grass species' with the exception of *M. caerulea* (purple-moor grass), which was more easily identified

4.3.1.1 Statistical analysis.

Data from the two surveys (all grasses under one classification) were Arcsine transformed due to data being percentage cover, tested for homogeneity of variance with Levene's test, and analysed by a Mann-Whitney test to identify any differences in total vegetation cover between the two surveys (Zar, 1994). Data from the burnt section (n=282) and unburnt section (n=174) were tested separately.

4.3.1.2 National Vegetation Classification of survey data.

Samples were analysed by TABLEFIT version 1.0 (Hill, 1996) to identify vegetation types as recognized by the National Vegetation Classification (NVC) (see section 4.1.3). TABLEFIT gives the NVC community from the data given in each sample. Data were 100% cover with all default parameters of the program accepted. The plant community given was only accepted when the 'goodness-of-fit' was >50% as suggested by Hill (1996).

Data from all the samples from the unburnt section of the first survey (2000) were used; this would give a baseline from which regeneration or vegetation on the moor could be measured as it was assumed this vegetation community existed before the 1995 wildfire.

Data from the two surveys (2000 & 2005) on the burnt section of moor were also analysed by TABLEFIT, however, not all samples were used. The percentage of bare soil/peat cannot be used for the NVC, therefore samples with a percentage of bare peat were not included in the analysis by TABLEFIT. These samples were shown to influence the NVC, for example *C. vulgaris* cover of 10% and *Festuca spp* cover of 10% with the rest bare peat gave a classification of H1 but with a goodness of fit of only 48% (very poor) and not accepted.

Samples with a high percentage cover of *Polytrichum spp* were also omitted from TABLEFIT analysis as the NVC does not have a classification for *Polytrichum commune* (section 4.1.3) for example, a sample with 100% cover of *Polytrichum spp* was classified as M6 but only with a 36% 'goodness of fit' and was therefore not accepted.

The results from this analysis by TABLEFIT showed the number of samples on the burnt section of moor that had the same plant community as the unburnt section in 2000 and 2005.

4.3.1.3 Two-way indicator species analysis (TWINSPAN).

The percentage cover from the two surveys were also analysed using TWINSPAN (Vespan 111 Lancaster University 1998) to show vegetation communities on the moor. All species or cover types, except burnt stalks, were used as indicator species, using the percentage scale there were five cut levels at 20% intervals (0.1%, 20.1%, 40.1%, 60.1%, 80.1%), giving five levels of abundance of a species, which were then used in presence/absence form to make the classification within TWINSPAN (Kent and Coker, 1992). The minimum number of samples in end groups (sub-communities) was selected to be six and the results displayed in dendrograms. This produced three data sets with three dendrograms, i) The year 2000 survey with plant species identified separately, ii) and iii) the 2000 and 2005 samples with most grasses and *E. vaginatum* grouped as one.

Each end group or sub-community identified by TWINSPAN was assigned a different symbol and with data of their known position entered into MapInfo (MapInfo Professional V5.5) and plotted on to a map of Darwen Moor to show vegetation sub-community distribution.

4.4. *PEAT DEPTH AND ASSOCIATED PLANT SPECIES.*

An investigation into the possible association between regeneration of plant species and peat depth was undertaken at the same sample sites at the same time as the full site vegetation surveys (section 4.3.1). Measurements were taken by inserting a 0.75m metal rod into the peat at the bottom right-hand corner of the each quadrat (n=456) until it reached the hard underlying strata or full length of the rod was inserted.

A contingency two-way chi-square test was performed on the peat depth and vegetation sub-communities to show any association. Only data from the burnt section of the moor were used, data were analysed from both surveys (for 2000 and 2005, all grasses and *E. vaginatum* were combined under one classification).

4.5 *RESULTS AND DISCUSSION OF SURVEYS*

4.5.1 Vegetation and ground cover composition on Darwen Moor from full site surveys.

The results from the Mann-Whitney test showed there was a significant difference between survey dates in total vegetation cover recorded on the burnt section of the moor ($P<0.05$), with no significant difference recorded in total plant cover between the first and second surveys on the unburnt section of the moor ($P>0.05$).

The results of the two surveys in the burnt section of moor are shown in Figure 4.1 The main cover changes are:- *C. vulgaris* had increased by 20%, *Polytrichum spp.* by 9%, with both bare peat and grass species showing a decrease in cover of 14%.

A classification described as 'non-moorland species' was set up to accommodate all those vegetation species not normally associated with moorland vegetation communities, for example *Chamerion angustifolium* (rosebay willowherb). This vegetation species classification included vegetation alien to the moorland and/or to the British Isles.

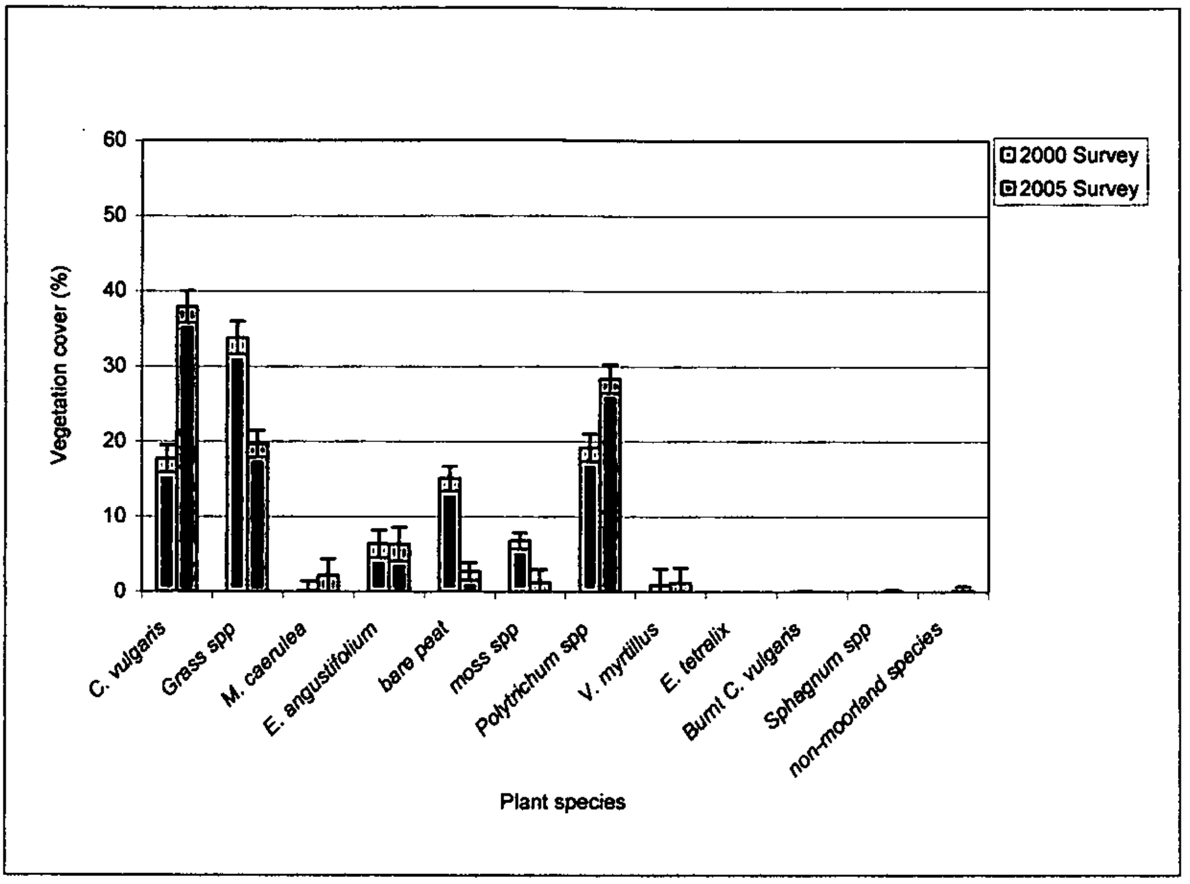


Figure 4.1 Results of vegetation and ground cover surveys on the burnt section of Darwen Moor completed in autumn 2000 and 2005. (Mean ± SE, n=282, one classification for most grasses and *E. vaginatum*).

Results from the unburnt section of moor (Figure 4.2) show a decrease in percentage cover of *C. vulgaris* by 9% and *E. tetralix* by 5%. Increases in grass spp, *M. caerulea* and *E. angustifolium* are 8, 3, and 9% respectively. Two new cover types recorded in the 2005 survey but not in the 2000 survey were *Polytrichum spp.* (3%) and bare peat 0.5%).

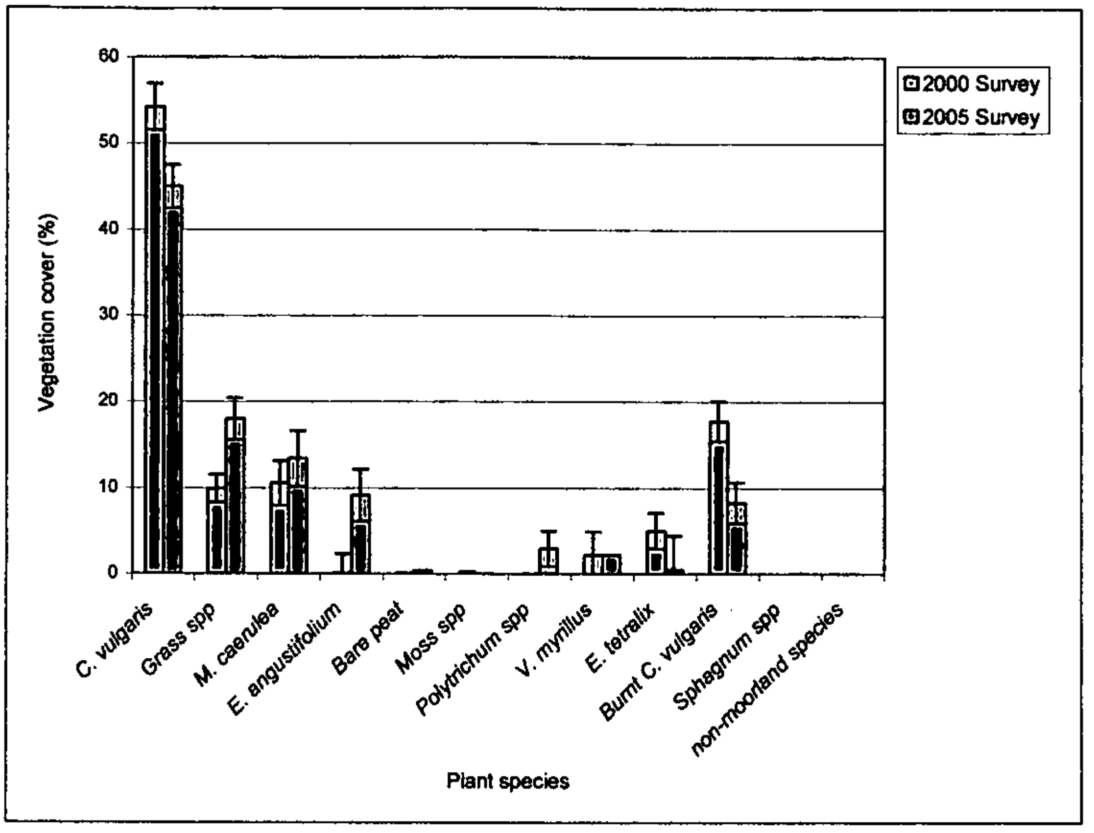


Figure 4.2 Results of vegetation and ground cover surveys on the unburnt section of Darwen Moor completed in autumn 2000 and 2005. (Mean ± SE, n=174, one classification for most grasses and *E. vaginatum*).

4.5.2 Results of National Vegetation Classification.

Results from analysis using TABLEFIT on data from the unburnt section of Darwen Moor showed that 74% of the samples were classified as H9. Other classifications, M16, U6 and M25 were generally a poor or very poor 'goodness of fit' and therefore the classification was not accepted.

The NVC of H9 (*C. vulgaris – D. flexuosa* heath) is described by Rodwell (1991) as sub-shrub vegetation of acid and impoverished soils at low to moderate altitudes with much of its character derived from a combination of frequent burning and grazing with heavy atmospheric pollution around the industrial conurbation of the Midlands and northern England. This plant community ranges from south Lancashire to the North York Moors. Rodwell (1991b) also explains the acid and impoverished soils which support this plant community have developed from Millstone Grit which in central Lancashire may have associated coal measures; all this fits with the description Darwen Moor, its vegetation and its underlying strata (see section 2.3). This also describes the desired vegetation and habitat of the moor and gives a base line from which regeneration of *C. vulgaris* can be measured.

As discussed in section 4.3.1.2 not all samples from the burnt section of moor were analysed using TABLEFIT. Results from the remaining samples show that in 2000, at the time of the first survey, 16% of the total samples from the burnt moor had the same classification (H9) as the unburnt section of moor; in 2005 this had risen to 40%.

Other classifications given by TABLEFIT were U1 and U2, which are *Festuca* and *Deschampsia* grasslands, both of which occur naturally in British uplands (Averis 2004). U1 grassland occurs on thin, dry, acid soils and U2 on base-poor moist, free-draining soils. In the first survey (2000) 25% of the total samples on the burnt section of moor were U1 or U2, in the section survey (2005) this had fallen to 18%.

4.5.3 TWINSPAN.

i) *2000 survey – individual grass species.*

From survey data (n=456) of the whole moor, eleven sub-communities were identified by TWINSPAN (Figure 4.3). The three largest sub-communities were *C. vulgaris* (135 samples/quadrats), Bare peat (73) and *Polytrichum spp.* (52). These data were used for the determination of permanent quadrat positions.

ii) *2000 survey. – grass species classified as one.*

This TWINSPAN analysis used the same data as i) but with all grass species and *E. vaginatum* combined. From the nine sub-communities identified the three largest sub-communities were *C. vulgaris* (114 samples/quadrats), Grass spp (111) and bare peat (81) (Figure 4.4).

iii) *2005 survey - grass species classified as one.*

Ten sub-communities were identified by TWINSPAN from the second survey data *C. vulgaris* (163 samples/quadrats) grass spp (72) and *Polytrichum spp.* (76) quadrats were the three largest sub-communities (Figure 4.5)

The largest changes between the two surveys (2000 and 2005 grass species as one category) were decreases in bare peat and moss species from 81 to 21 samples, grass *spp.* from 111 to 72 samples and burnt *C. vulgaris* stalks from muirburns from 40 to 11 samples. An increase in *C. vulgaris* (114 to 163) and *M. caerulea* (21 to 39) was recorded.

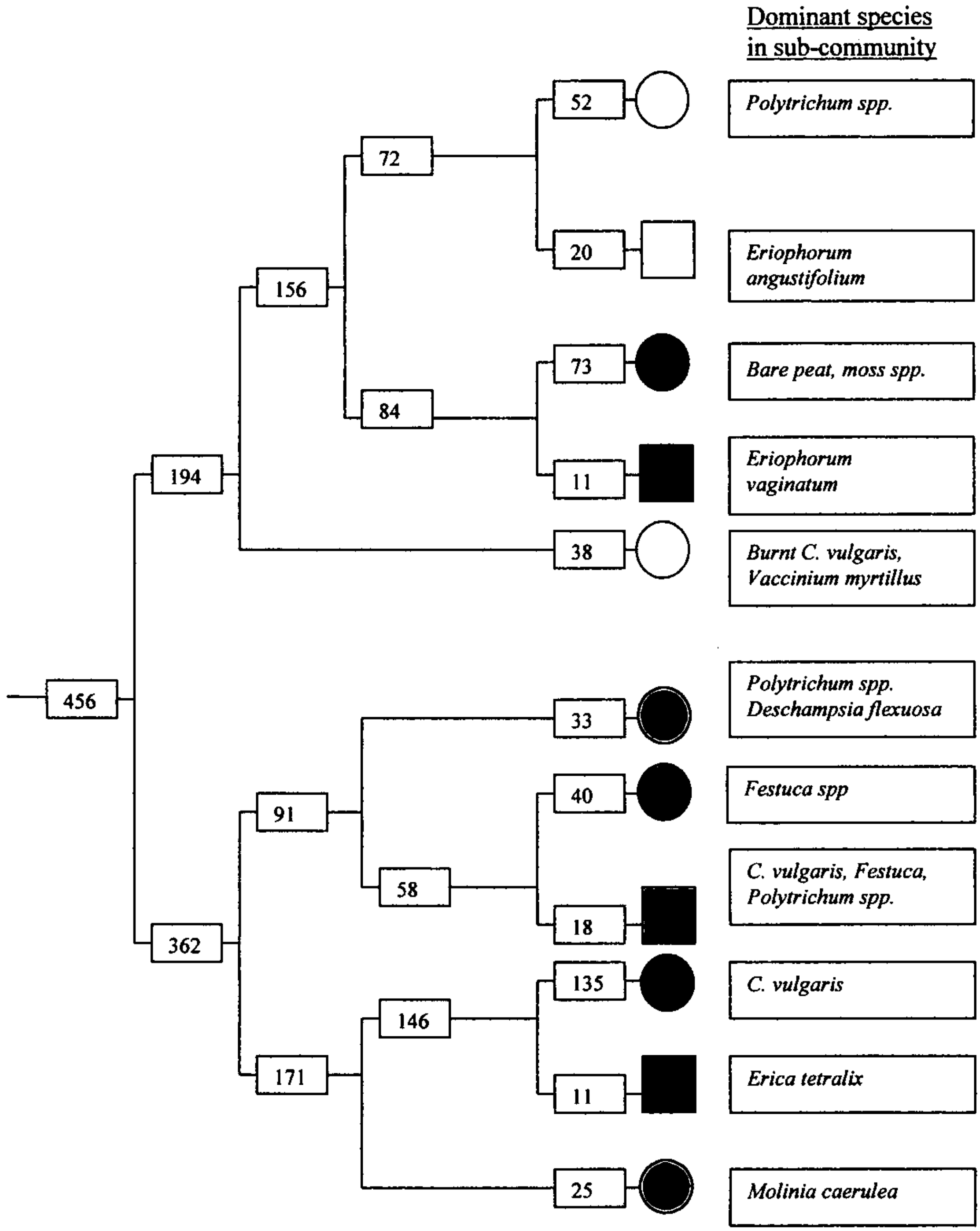


Figure 4.3 Vegetation sub-communities identified by TWINSPAN. Data are from a vegetation survey of the whole of Darwen Moor (2000); grass species are individually classified (n=456). $\boxed{n}$ = number of samples/quadrats

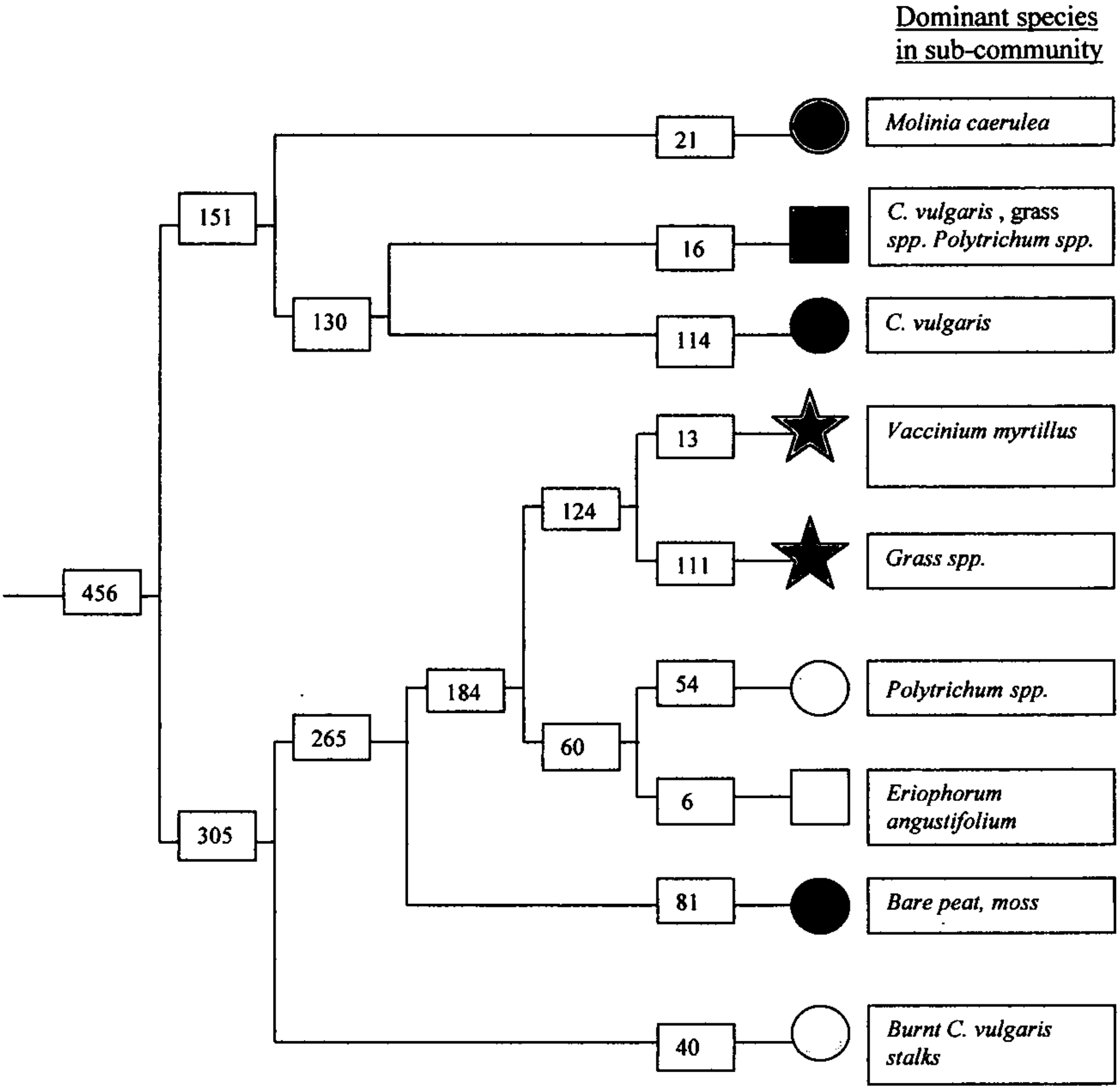


Figure 4.4 Vegetation sub-communities identified by TWINSPAN. Data are from a vegetation survey of the whole of Darwen Moor (2000); all grass species and *E. vaginatum* are classified under one group (n=456). $\boxed{n}$ = number of samples/quadrats.

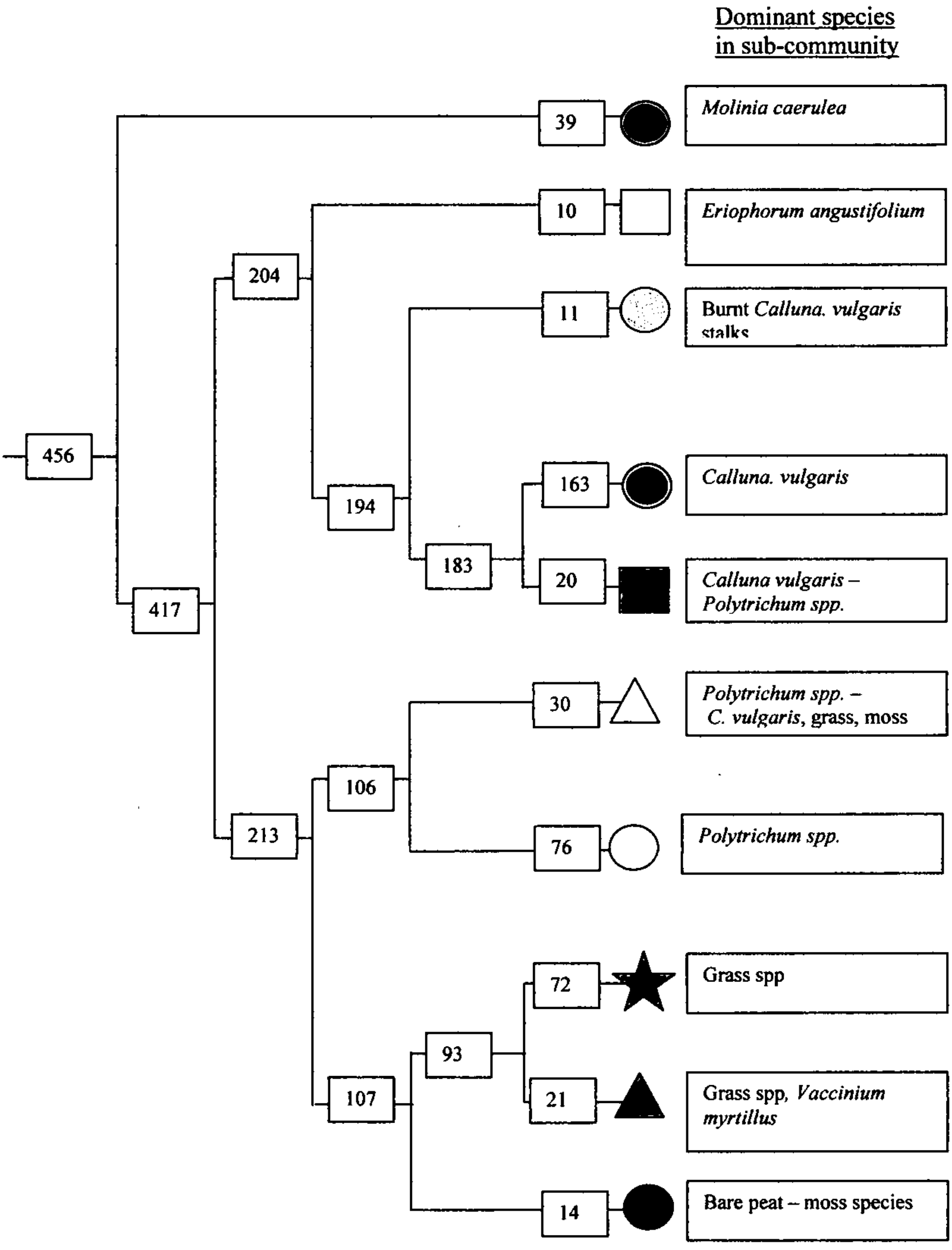


Figure 4.5 Vegetation sub-communities identified by TWINSPAN. Data are from a vegetation survey of the whole of Darwen Moor (2005); all grass species and *E. vaginatum* are classified under one group (n=456). $\boxed{n}$ = number of samples/quadrats.

4.5.4 Peat depth and plant association.

Results from the two contingency tables using data from the two surveys on the burnt section of Darwen Moor (grass species under category) are:-

2000 survey = $\chi^2/_{49}$ = 71.63, (P<0.05)

2005 survey = $\chi^2/_{21}$ = 36.55, (P<0.05)

Results were calculated from data where the 'expected' frequencies were not below one and fewer than 20% of the grand- total had 'expected' frequencies below five (Fowler *et al.* 1998).

This analysis shows that there is a statistically significant association between certain plant species and the depth of peat at both samples times. The largest positive association was between bare peat and the moss sub-community on peat >70cm deep, with a negative association on shallow peat. The largest negative association was found between grass species and peat >70cm deep, again with a corresponding association on peat up to 60cm deep. These associations are shown on the maps of Darwen Moor (Figure 4.6 and 4.7); bare peat (black circle) is predominately in the south where the peat is deep (black circle). Grass species (green circles) are on the shallow peat in the north section of the moor.

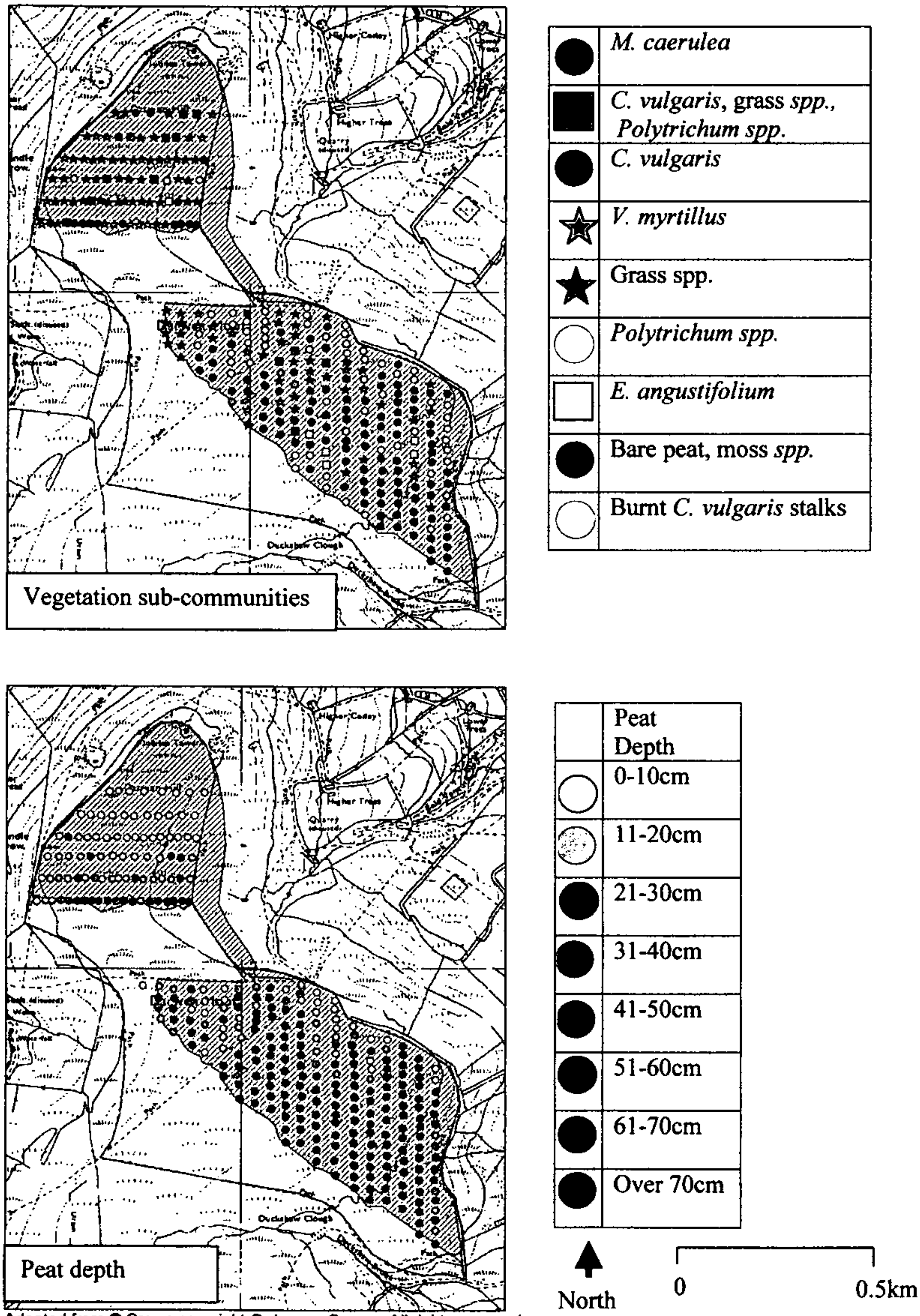


Figure 4.6 Vegetation sub-communities and peat depth at each sample site (burnt section) in 2000 survey (one classification for grasses and *E. vaginatum*).

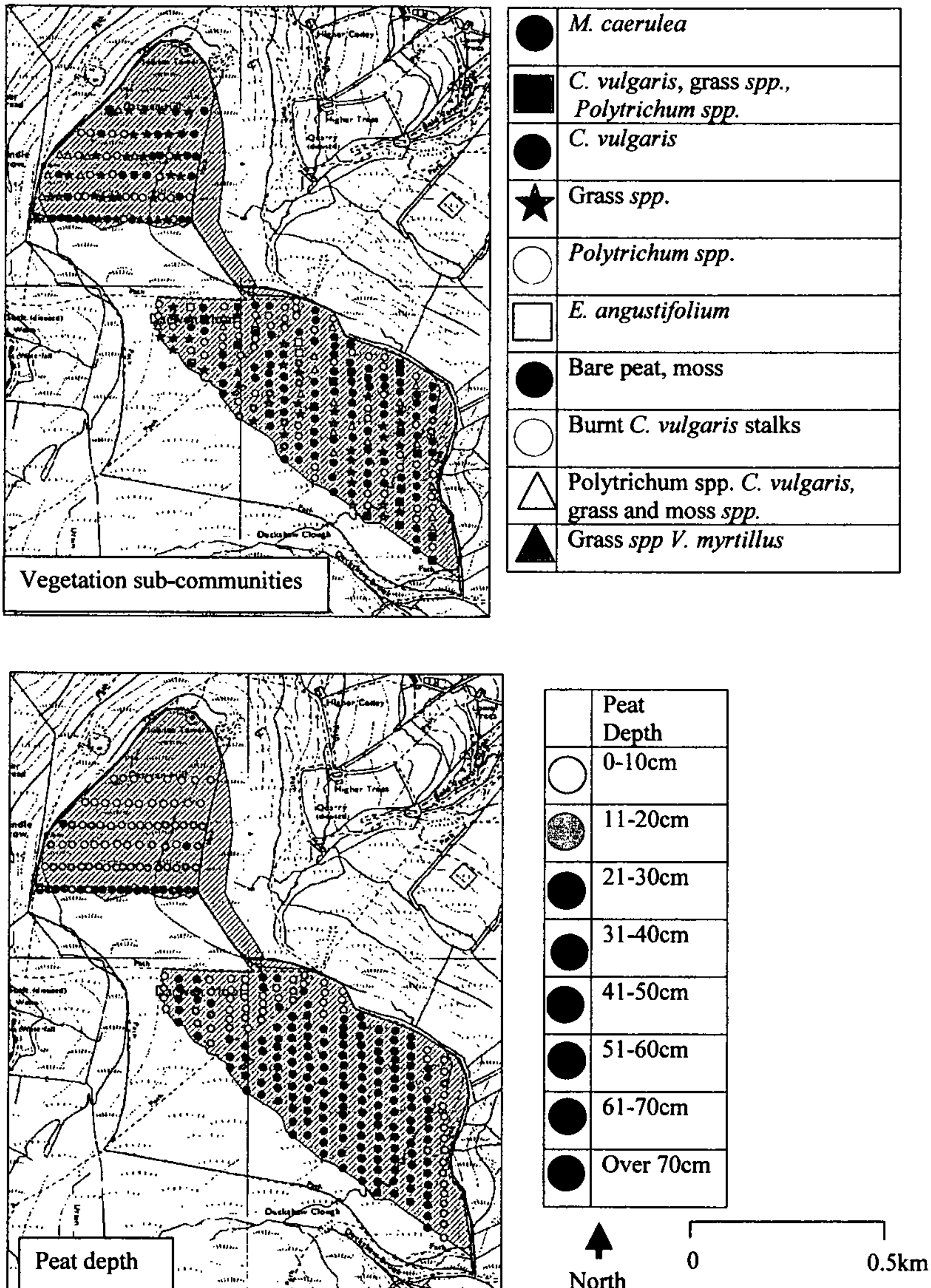
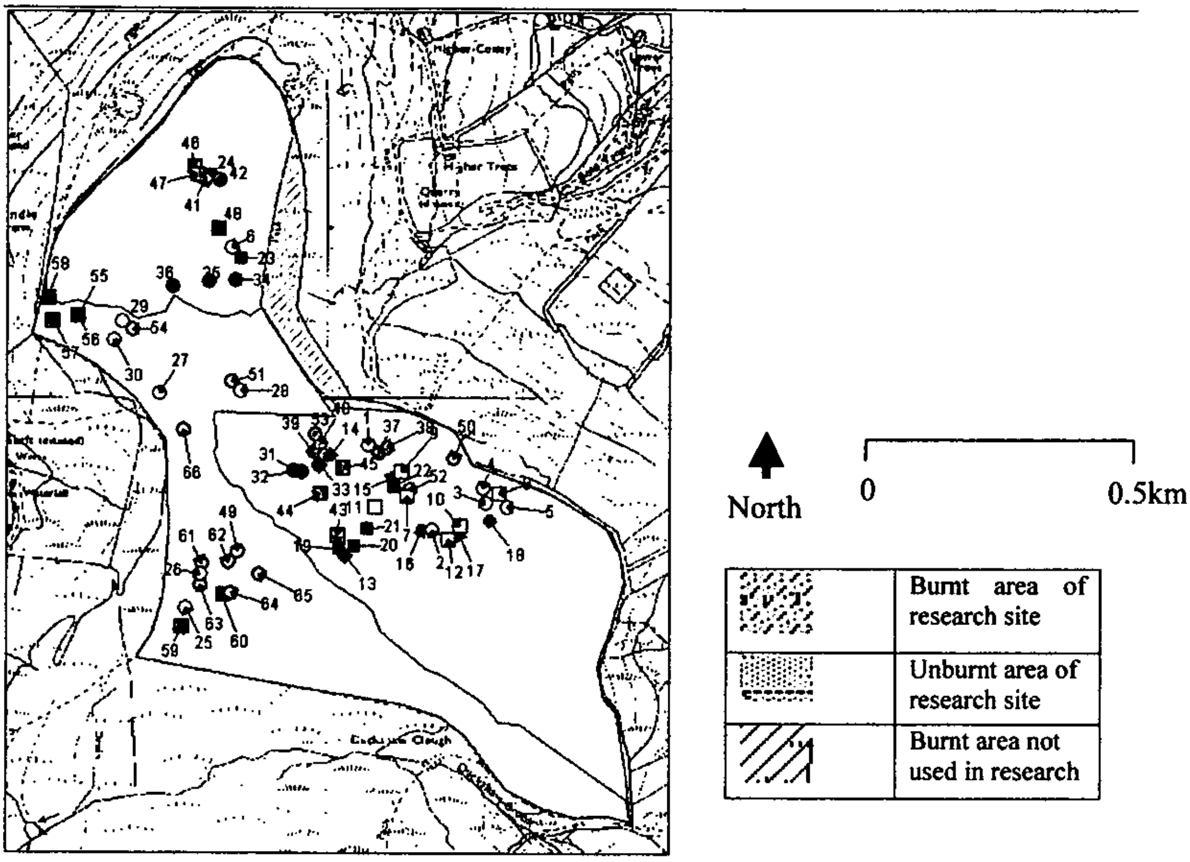


Figure 4.7 Vegetation sub-communities and peat depth at each sample site (burnt section) in 2005 survey (one classification for grasses and *E. vaginatum*).

4.6 *PERMANENT QUADRATS.*

4.6.1 Materials and methods.

Using all sub-communities (n=11) as identified from TWINSPAN analysis (plant species identified individually) from data of the first vegetation survey of Darwen Moor (section 4.3.1.3) and their relative position on the moor, sites for permanent quadrats were selected. These sites were carefully selected to fit the sub-community and plant composition as identified by TWINSPAN. Six quadrats per sub-community were placed on the moor, giving a total of sixty-six permanent quadrats (Figure 4.8). Each quadrat of $1m^2$ was marked with small metal pegs through a washer (4cm diameter) pushed into the ground at each corner; one peg was also marked by a short piece of coloured string. The grid reference of each quadrat was also recorded (see Appendix 3). Location of the permanent quadrats at monitoring was by grid reference using the 'go to' function on a handheld GPS, sight and by metal detector (Viking 5, Viking Metal Detectors, Darwen, Lancs.) if sighting of coloured string and pegs were obscured by vegetation. These methods and precautions ensured quadrat security, due to the site being open to the general public; also in case of fire (muirburn or accidental) quadrat positions would not be lost. All sections (burnt and unburnt) of the moor were included as a control to monitor any change in vegetation due to climatic changes or potentially from another severe fire. Permanent quadrats placed on the burnt section of moor were within the area that received post-fire management.



Sub-community	Quadrat number	Symbol
Polytrichum spp	1-6	
E. angustifolium	7-12	
Bare peat, moss species	13-18	
E. vaginatum	19-24	
Burnt C. vulgaris, V. myrtillus	25-30	
Polytrichum sp., D. flexuosa	31-36	
Festuca spp	37-42	
C. vulgaris, Festuca spp., Polytrichum spp.	43-48	
C. vulgaris	49-54	
E. tetralix	55-60	
M. caerulea	61-66	

Figure 4.8 Permanent quadrat positions on Darwen Moor and their associated sub-communities.

4.6.2 Monitoring of permanent quadrats.

Most vegetation surveys are completed during the growing season however, due to the moor being used for grouse breeding and important for other nesting birds, surveys could not be completed in the summer months. It was therefore decided to undertake two surveys, in spring and autumn of each year (2002-2005). Spring surveys were completed by 15th April (end of the muirburn or management burn season). Autumn surveys were completed as described in section 4.3.1. This ensured that monitoring of the permanent quadrats was carried out at approximately the same period of vegetation growth/die back and no birds were disturbed.

The spring surveys were monitored by the photographic method, with visual percentage cover estimated using Adobe PhotoShop 6.0 computer program, as described in section 3.3.1.1. The autumn surveys also consisted of a photographic survey but with the addition of a point quadrat survey. Within a 1m^2 quadrat, one hundred points were used with the upper canopy cover being recorded: i.e. first hit only scored, to give a 100% cover (either vegetation or bare peat), as described in section 3.3.2.

Due to problems of grass identification, as discussed in section 4.3.1, most species of grass and *E. vaginatum* were included in one classification. Where muirburn management had occurred and burnt *C. vulgaris* stalks were present these were classified separately. All low ground-covering cushion moss species were also classified as one.

As discussed in Chapter 3, the photographic method of data collection of vegetation cover was evaluated against the more traditional method of point quadrat and from two trials was shown to as accurate. The point quadrat method of surveying the permanent quadrats was included in this study along with the photographic method, so these two methods could be evaluated in a much long timeframe.

4.6.3 Statistical analysis.

All data were arcsine transformed due to the recorded vegetation cover of 100% (Zar 1995). An ANOVA with repeated measures using the SPSS statistical package (Version 10.0) was used to test differences in vegetation cover between sample times in each sub-community. The assumption of sphericity in repeated measures ANOVA was overcome by using the Greenhouse-Geisser adjusted P value (Kerr *et al.* 2002). Spring and autumn data were analysed separately.

Figures with mean percentage cover for each plant species or bare peat in each sub-community (n=6), with standard error, were produced to show the change in cover over the four years of monitoring (spring and autumn analysed separately) (see Appendix 4).

An ANOVA with repeated measures was also used to test differences in vegetation cover between the two sampling methods (point-quadrat and photographic) used in the autumn surveys.

4.6.4 Detrended Correspondence Analysis (DECORANA).

DECORANA was used to examine the data (Vespan 111 Lancaster University 1998). DECORANA groups samples with a similar vegetation composition together, and was used to detect changes in vegetation composition in each sub-community during the study period. Each axis produced by DECORANA has an associated eigenvalue that indicates the degree to which the axis captures the variation within the sampling points. A value of 1 would indicate perfect capture; a value of zero indicates no representation at all, axis 1 was plotted against axis 2 to give best representation. Each quadrat was plotted on the Figure in year series; a separate Figure was produced for each sub-community at spring and autumn sampling times.

4.7 RESULTS OF PERMANENT QUADRATS.

No significant differences ($P>0.05$) were recorded in vegetation cover in any of the sub-communities from the four years of monitoring in either of the spring or autumn surveys except for quadrats 55-60, *E. tetralix* sub-community at the autumn survey. Here grass species and *M. caerulea* had become more dominant than *E.tetralix.*

Figure 4.9 and 4.10 are examples of images of permanent quadrats over four years of monitoring.

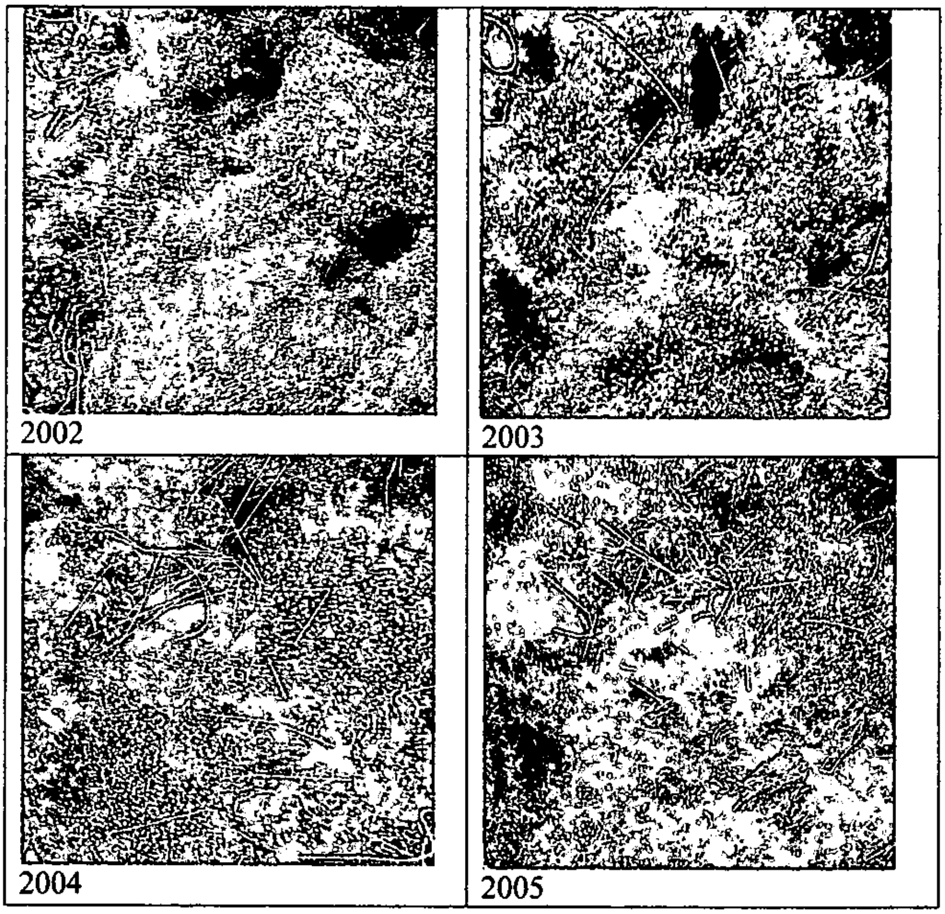


Figure 4.9 Autumn series of permanent quadrat 5 (*Polytrichum spp*). In this series *C. vulgaris* cover can be seen to be increasing (bottom left of images) within a bed of *Polytrichum spp.* When estimating vegetation cover in Adobe Photoshop the images would be enlarged.

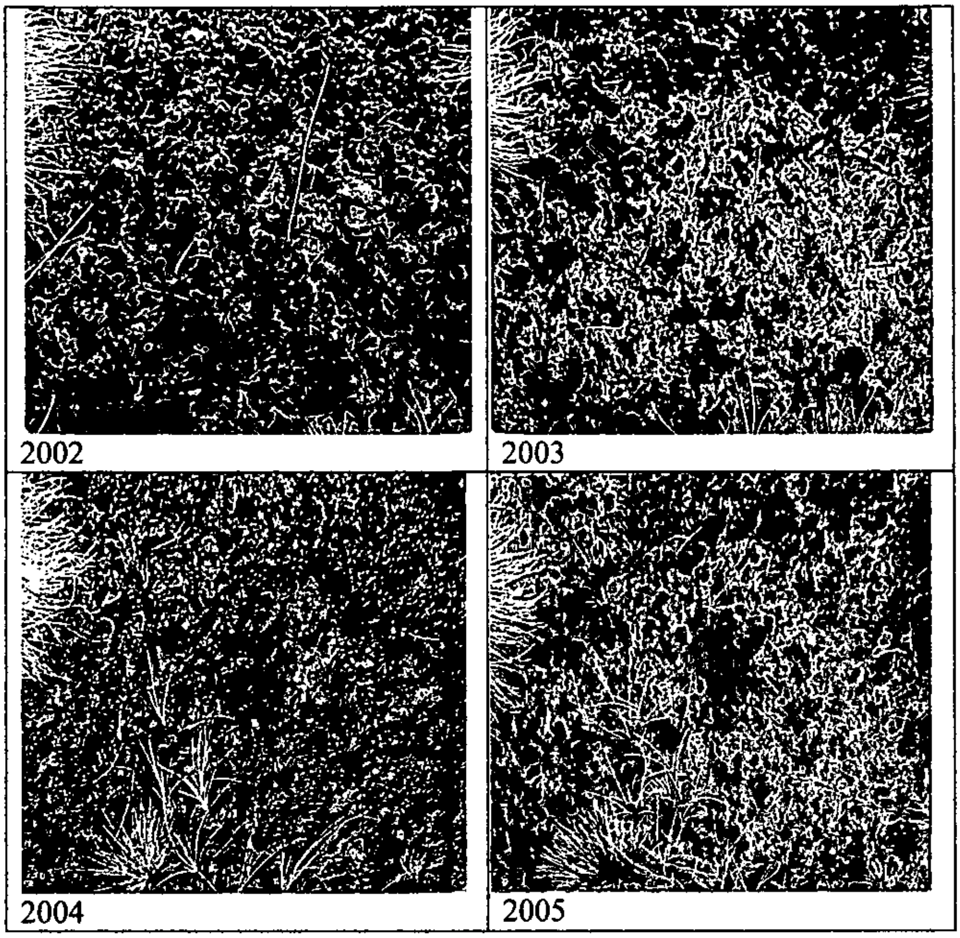


Figure 4.10 Autumn series of permanent quadrat 13 (Bare peat). These series shows a varying percentage cover of small mosses, but an increase of cotton grasses over the four years of monitoring. When estimating vegetation cover in Adobe Photoshop the images would be enlarged.

Results from the ANOVA showed there were no significant differences ($P>0.05$) in vegetation cover between the two sampling methods (photographic and point quadrat) used in the autumn surveys, which confirms the results of chapter 3.

Only two permanent quadrats were lost, one in the *Polytrichum spp* (1-6), and another in the *Polytrichum* and grass quadrats (30-36) where the vegetation had become too deep for the metal detector to find the pegs. Two quadrats were damaged from a management burn, although all vegetation was removed, the pegs survived and monitoring was possible.

Only some of the more interesting results are presented here, full results from permanent quadrat monitoring (spring and autumn) and results from DECORANA are provided in appendices 4 and 5.

Major changes in vegetation composition on Darwen Moor over the four years of monitoring permanent quadrats are shown in Table 4.0.

Eight of the eleven sub-communities (not including that of the *C. vulgaris*) showed an increase in percentage cover of *C. vulgaris*; for example an increase of 38% recorded in quadrats 7-12 (*E. angustifolium*). *C. vulgaris* cover in it own sub-community remained relatively unchanged at 98% (Table 4.0).

Grass cover varied over the sub-communities; where *Polytrichum spp.* were present (quadrats 1-6, 31-36, and 43-48) there was a marked decrease in grass cover. In other sub-communities (quadrats 7-12, 13-18 and 55-60) an increase of grass cover was recorded (Table 4.0).

Polytrichum spp. cover increased in five of the sub-communities including its own sub-community; no decrease in cover was recorded in any sub-community (Table 4.0).

The bare peat and moss spp sub-community (quadrats 13-18) showed a decrease in the amount of bare peat recorded over the four years of sampling with grass and *C. vulgaris* the largest colonisers although *Polytrichum spp.* represented some cover (9% spring and 11% autumn) (Table 4.0 and Appendix 4).

In quadrats 25-30, (burnt *C. vulgaris, V. myrtillus*), the bare peat was replaced by new *C. vulgaris* plants with a reduction of 60% of bare peat over four years (Table 4.0).

Table 4.0 Major changes in mean vegetation cover (%) within sub-communities between 2000 and 2005, only changes >1% are displayed. (Other changes of vegetation cover i.e. cotton grass not included). S=Spring, A=Autumn Survey.

Sub-community		*C. vulgaris*	Grass	*Polytrichum spp.*	Bare peat
1 – 6 *Polytrichum spp.*	S	+ 3	-4	+6	
	A	+ 4	-1	+2	
7 – 12	S	+25	+15	+3	
E. angustifolium	A	+38	-5	+8	
13 – 18	S	+4	+ 15	+5	-34
Bare peat, moss *spp*	A	+17	+15	+4	-22
19 – 24	S				
E. vaginatum	A				
25 – 30	S	+26	-2		-60
Burnt *C. vulgaris*, *V. myrtillus*	A	+24	+4		-45
31 – 36	S	+11	-53	+42	
Polytrichum spp. Grass spp.	A	+13	-26	+15	
37 – 42	S	+17	-25		
Grass *spp*	A	+34	-41		
43 – 48	S	+23	-28	+4	
C. vulgaris, grass *spp*, *Polytrichum spp.*	A	+24	-30	+7	
49 – 54	S				
C. vulgaris	A				
55- 60	S	+10	+16		
E. tetralix	A	+3	+31		
61 – 66	S				
M. caerulea	A				

Four sub-communities showed little change from the original vegetation cover: - *Polytrichum spp.* (quadrats 1-6), *E. vaginatum* (quadrats 19-24), *C. vulgaris* (quadrats 49-54) and *M. caerulea* (quadrats 61-66) (Table 4.0). Figure 4.11 is an example of a sub-community which is very stable and has changed little over the four years of monitoring, although it does show *Polytrichum spp.* and *C. vulgaris* were replacing grass spp, bare peat, *E. vaginatum* and non-moorland species.

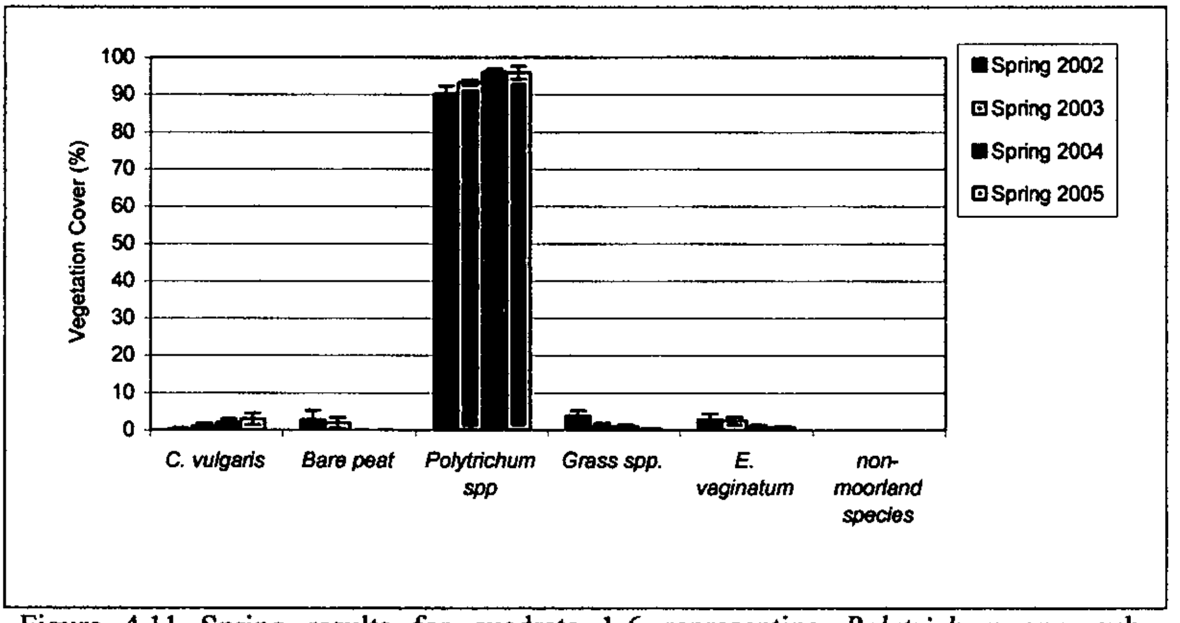


Figure 4.11 Spring results for quadrats 1-6 representing *Polytrichum spp.* sub-community. (Data mean vegetation cover, n=6 ± SE).

4.7.1 Seasonal vegetation changes.

There were changes in percentage cover of vegetation in some sub-communities between spring and autumn monitoring, for example in quadrats 13-18 representing the bare peat and moss *spp* sub-community, there was less bare peat but more grass cover in the autumn survey (Figure 4.12).

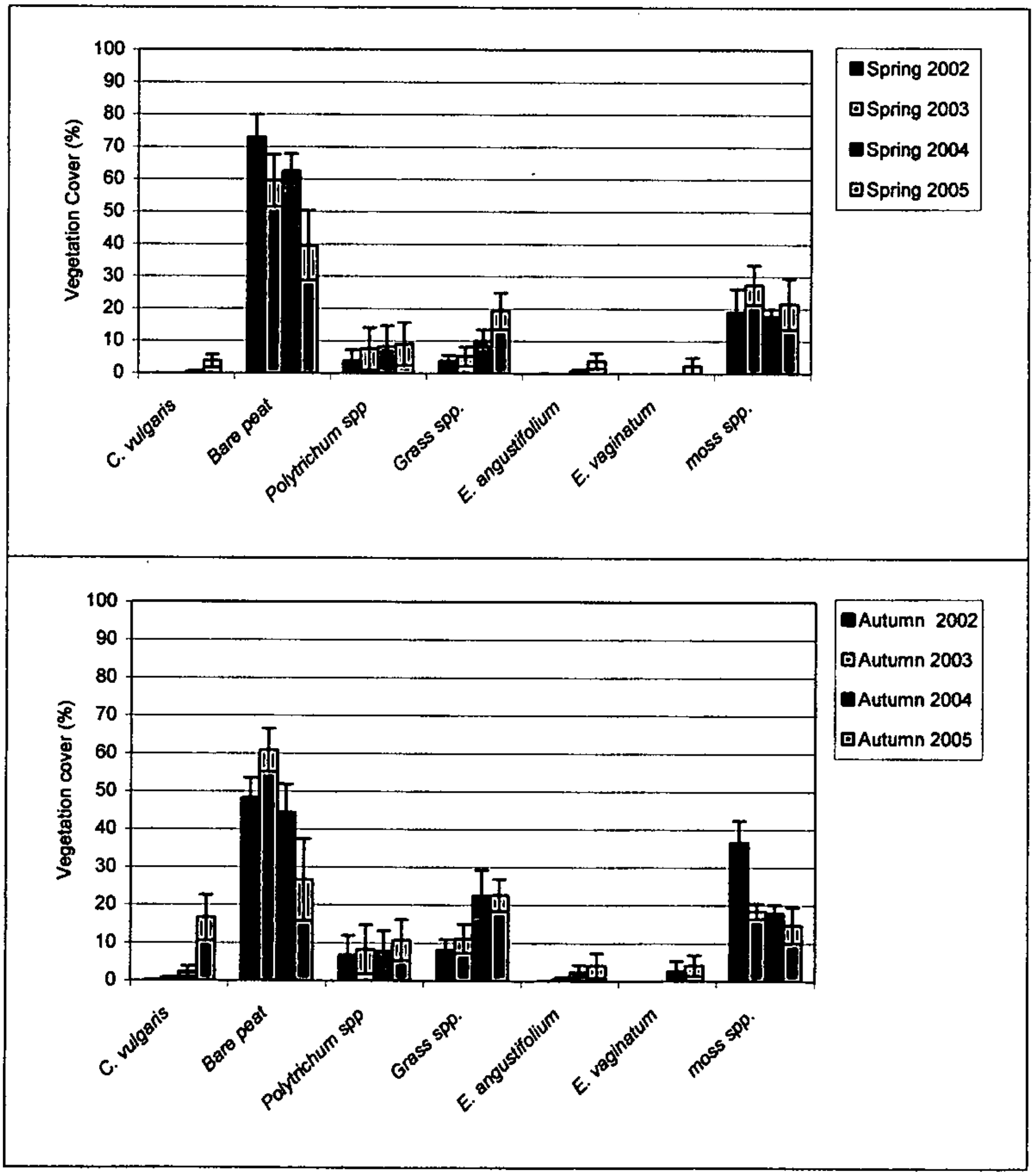


Figure 4.12 Results from monitoring permanent quadrats 13-18 (sub-community – bare peat and moss *spp.*) for four years (2002 – 2005). (Mean ± SE).

4.7.2 DECORANA results.

DECORANA analysis showed directional trends in vegetation composition were generally absent within the permanent quadrats. Examples of figures produced from the first two axis of DECORANA are illustrated in figures 4.11 – 4.13, (different scales on the graphs are used so change in vegetation composition can be seen). All plots are samples with different colours representing different years; a full set of DECORANA results are provided in Appendix 5.

Figure 4.13 is an example where a slight directional trend is shown in quadrats 43 – 48 (sub-community - *C. vulgaris,* grass spp and *Polytrichum spp.*)

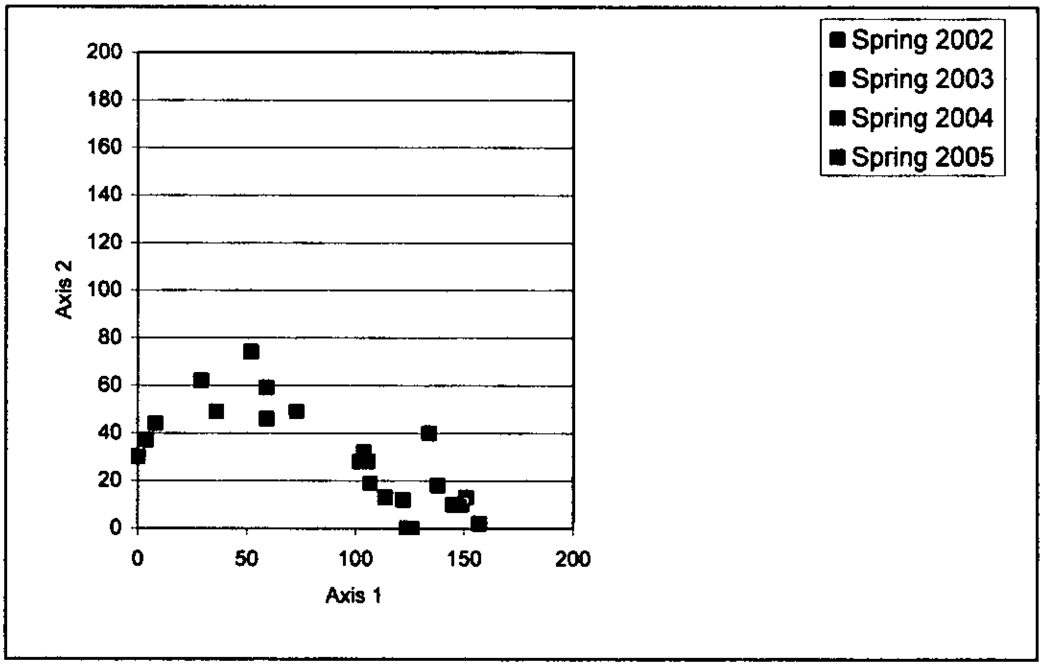


Figure 4.13 DECORANA results for quadrats 43-48 (sub-community - *C. vulgaris,* grass spp and *Polytrichum spp.*).

In quadrats 7-12 (sub-community *E. angustifolium*) the DECORANA results show that the vegetation composition of the quadrats had changed. In year one (blue) all the quadrats were very similar; by year four (red) quadrats were varied (Figure 4.14)

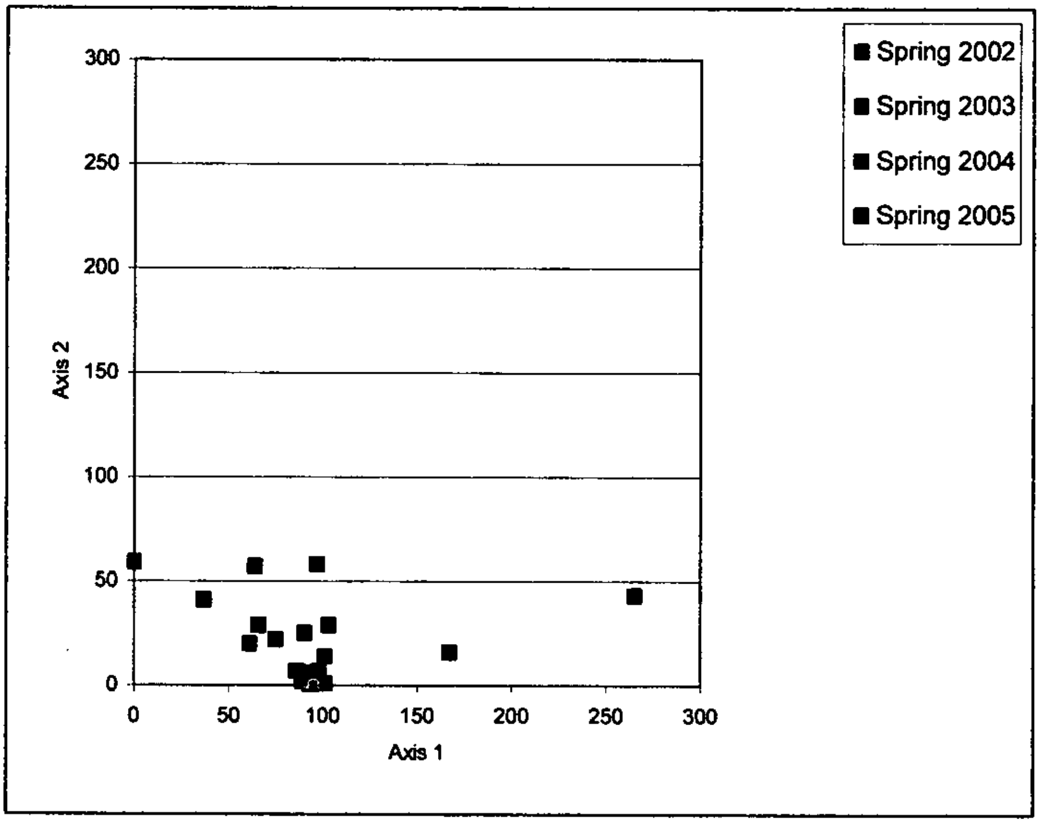


Figure 4.14 DECORANA results for quadrats 7-12 (*E. angustifolium* sub-community).

Three sub-communities:- *Polytrichum spp.* (quadrats 1-6), *E. vaginatum* (quadrats 19-24), *C. vulgaris* (quadrats 49-54) and *M. caerulea* (quadrats 61-66) changed very little in their vegetation cover; Figure 4.15 is an example of DECORANA results to illustrate this (change of axis scale).

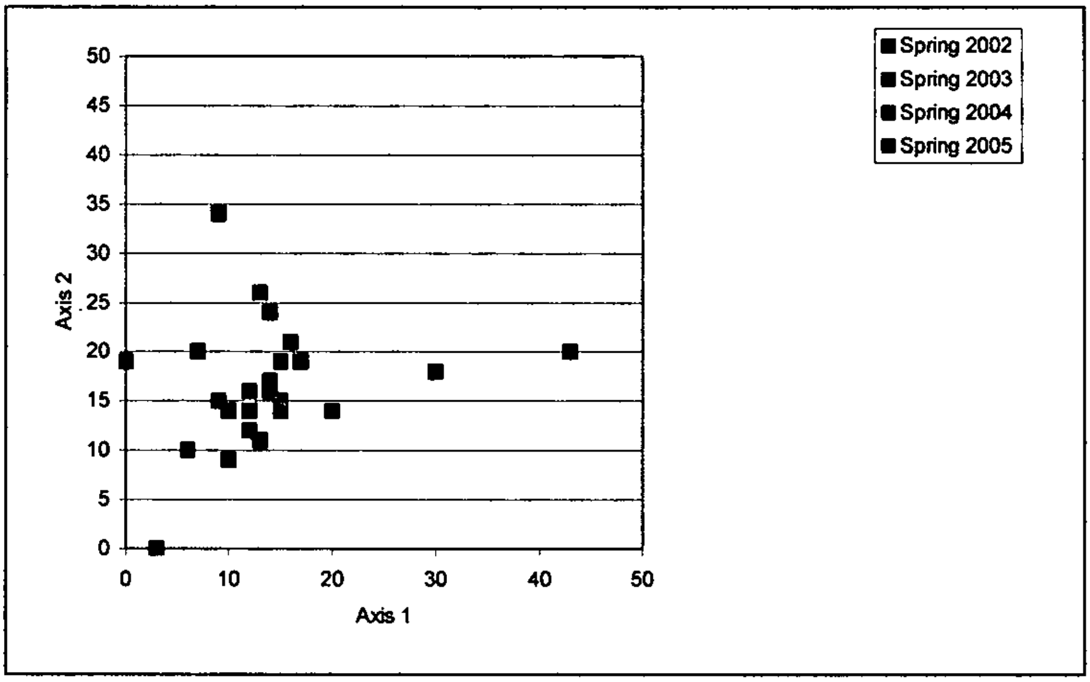


Figure 4.15 DECORANA results for quadrats 1-6 (*Polytrichum spp*).

4.8 *DISCUSSION.*

The NVC of the unburnt section of the moor suggests pre-wildfire vegetation on Darwen Moor was H9 H9 (*C. vulgaris – D. flexuosa* heath), with 74% of samples given this classification (2000). This base-line classification was compared with results from the burnt section in both surveys (2000 and 2005). Results showed that in 2005, ten years after the wildfire, 40% of samples from the burnt section were now classified as H9, this was an increase from 16% in 2000. This was also confirmed by analysis of the total vegetation cover of the burnt section of the moor ,which showed an increase of *C. vulgaris* cover from 17% to 38% (2000 and 2005) (figure 4.1).

Results from the full vegetation survey in the burnt section also showed that grass species had declined from 35% to 19% although it is unknown if all or any these grass species were from the seeded nurse species. Their decline and the subsequent increase in cover of *C. vulgaris* suggest there was a positive effect from the nurse species, something that has also been reported by Bradshaw (1997), Whisenant (1999) and Gretarsdottir *et al.* (2004). This decline in sown species was however not as rapid as that reported by Greipsson and El-Mayas (1999). On a 10-year-old site in Iceland the seeded grass species disappeared leaving a high cover of plant litter and a low cover of native herbs. Nevertheless, results from the unburnt section of Darwen Moor show grass cover was 10% in 2000 so it must be assumed that grass species were always present. This reduction in grass cover was also recorded in the permanent quadrats, although grass cover did increase in the bare peat and moss sub-community (quadrats 13-18).

The reduction of bare peat from 100% post-wildfire (1995) (section 2.3) to 15% and 3%, 2000 and 2005 respectively may show that post-wildfire management facilitated the revegetation of the moor. This trend was also recorded in the permanent quadrats (13-18 bare peat, moss species) where grass, *C. vulgaris* and *Polytrichum* had become the dominant species. However, this continued reduction of bare peat is almost certainly from natural colonisation with plant species able to take advantage of the improved conditions. With surrounding vegetation able to act as trap seeds (Nathan and Muller-Landau 2000) small bare areas can be quickly revegetated because of increased numbers of propagules (Miles 1979).

Results from the permanent quadrats (2001-2005) were not significant, showing that four years of monitoring are not sufficient to record any change in vegetation cover of the sub-communities identified on Darwen Moor. Therefore, only trends in vegetation change within the permanent quadrats and what these may imply can be discussed. This is in contrast to the full site survey on the burnt section where a significant difference ($P< 0.05$) in vegetation was recorded.

Methods for marking the permanent quadrats proved successful, only a few quadrats were lost, mainly due to depth of vegetation covering the metal pegs, which was even too deep for the metal detector to find. Two permanent quadrats (sub-community *E. tetralix*) were in an area that was re-burnt in a muirburn, string markers were lost but quadrats were successfully located by use of the metal detector. It was within this sub-community that the only significant difference in vegetation cover was recorded.

Polytrichum increased in cover on the burnt section of moor from 19% to 28%, the trend from the permanent quadrat results suggested it was the grass species that were inhibited and not *C. vulgaris*. *C. vulgaris* had increased cover in both of the sub-communities where *Polytrichum spp.* was present (quadrats 1-6 and 31-36). This was in contrast to findings of Clement and Touffet (1990) who suggested that if *Polytrichum* species became the dominant vegetation on regenerating moorland, growth of *C. vulgaris* would be inhibited. Two of Connell and Slatyer's (1977) models of succession may be illustrated here; sown grass species have changed the environment by reducing nutrients and stabilising the peat, which made it less favourable for grass species but more favourable for *Polytrichum spp* and *C. vulgaris* (Facilitation model). *C. vulgaris* may also be inhibiting *Polytrichum spp.* by competition for light (Inhibition model).

The vegetation composition on the burnt moor became more varied in terms of percentage cover of plant species with different sub-communities, but not necessarily more diverse as there were few new plant species on the moor. TWINSPAN analysis suggested there were nine sub-communities in 2000 and ten in 2005 (when grass species and *E. vaginatum* were grouped as one). New species recorded on the moor and classified as 'non-moorland species' were *Chamerion angustifolium* (rosebay willowherb), *Aster novi-belgii* (michaelmas daisy) and fern species. Trees were not included in the calculation of cover but a few species, included *Sorbus aucuparia* (rowan) and shrub willows (*Salix spp.*), were beginning to establish. These plants are able to exploit the open substrate and become established (show an r-strategy); the early-successional willows are light-seeded and fast-growing and may have become dominate in the early stages of succession if it was not for the practice of the gamekeeper to remove them. Birds may bring the *S. aucuparia* seeds onto the moor from the surrounding rough pasture hedgerows. Early establishment of the trees may have been possible due to lack of grazing on Darwen Moor.

Results from DECORANA on data from the sub-communities showed the vegetation on Darwen Moor was not progressing uni-directionally, with increasing variation between the samples of the same sub-community. For example, figure 4.10 (*E. angustifolium* sub-community) shows the quadrats now have an almost equal cover of *C. vulgaris*, *Polytrichum*, grass and *E. angustifolium*. This may imply that environmental conditions are more suited to a variety of plant species, which may or may not inhibit or facilitate the regeneration of *C. vulgaris*. Short-term effects of grass seeding and fertilisation in Iceland on similar degraded sites have shown limited natural colonisation when the cover of seeded grasses and litter was still high (Gunnlaugsdottir 1982).

The very slow succession within the permanent quadrats may suggest there are factors that are limiting vegetation establishment and change. Bradshaw (1987) discussed rate-limiting factors in reclamation and classified them as physical, biological or chemical. Examples of these limiting factors are given by Roem *et al.* (2002) who have shown nitrogen, phosphorus, N:P ratio and pH have all have an effect on species composition in heathland.

The full site survey on the unburnt section suggests the vegetation status is stable with no significant change in cover being recorded. However, on this unburnt section there was a decrease in *C. vulgaris* cover (54 to 45%) and a corresponding increase in grass cover (10% to 18%). An explanation for this may be the muirburn management of the unburnt moor, which provided an opportunity for grass and other plant species to colonise the newly burnt moor. Muirburn may provide the disturbance required to facilitate the colonisation of grasses particularly if the *C. vulgaris* is old at time of management burn (MAFF 1994). *M. caerulea* is also a problem on the unburnt moor with an increase of 3% (10-13%); again some of this encroachment may be due to muirburn practices.

A difference within some sub-communities between spring and autumn monitoring was shown, however, this may be due to different plant properties i.e. die-back in winter or vigorous growth in the summer months. Results also showed an association between peat depth and vegetation colonisation on the burnt section of Darwen Moor, with grass favouring the shallower peat and more peat un-vegetated if peat was deeper than 70cm. One explanation for this may be that the post-wildfire management concentrated on the north section of the moor where the peat was shallower. However, most vegetation cover was also observed on the shallow peat or mineral soil on the Stalybridge site (appendix 1). Conditions that may prevent regeneration of vegetation of deep peat are investigated in chapters 5, 6 and 7.

The use of a point quadrat in addition to the photographic method of collecting sample data confirms the results of Chapter 3, that there was no significant difference ($P > 0.05$) between these two methods when used on low moorland vegetation.

In conclusion, *C. vulgaris* has begun to return to the burnt section of Darwen Moor with cover increased to 38% ten years after the wildfire. Grass species are being replaced by other vegetation, which suggests there was a positive effect of the sown nurse species although results suggest this change is very slow. There may be a problem from *Polytrichum spp* if they become dominant although *C. vulgaris* has been shown to increase cover within the *Polytrichum spp* sub-community. In 2005 bare peat only covered 3% of the area that was burnt in the 1995 wildfire. Although vegetation cover is changing, four years of monitoring the permanent quadrats has shown to be insufficient time to detect direction of vegetation change.

5.0 CHAPTER 5

GERMINATION AND ESTABLISHMENT OF *CALLUNA VULGARIS* ON MOORLAND PEAT POST-WILDFIRE.

5.1 *INTRODUCTION*

This chapter investigates germination and establishment of *C. vulgaris* seeds on peat where the physical properties of the peat may have changed due to biological, physical and chemical alterations induced by wildfire, in addition to subsequent exposure to the atmosphere.

5.2 *BACKGROUND TO THIS STUDY.*

5.2.1 Peat properties post-wildfire.

Crust formation has been observed on the surface of burnt organic soil (Maltby *et al.* 1990). This crust tends to create a solid barrier that is resistance to re-wetting (Mallik and Rahman 1985) and often heaves away from the underlying soils, breaking the hydraulic continuity (Maltby *et al.* 1990). Frost action may also separate the top layer of crust from the underlying peat surface (Maltby *et al.* 1990). Hard soils have also been implicated in poor seedling establishment due to failure of seed radicle penetration (Marschner 1995). As soils become drier, soil strength increases with more force required to break apart aggregates, which may inhibit plant root growth by prevention of root elongation, which may also lead to poor nutrient uptake (Marschner 1995). Although this crust may break down with time, natural revegetation is slow (Radley, 1965, Maltby *et al.* 1990, Gilchrist *et al.* 2004).

A blackened surface following fire and the subsequent un-vegetated peat may decrease the albedo of the soil (Thomas 1984), thus increasing surface temperature and evaporation rate, creating an unsuitable place for germination and growth, (section 6.4). In the absence of fire, surface organic matter, such as partially decomposed leaves, twigs and lichens, increase the water retention properties of the soil, which assists seedling regeneration of *C. vulgaris* (Mallik *et al.* 1988); but in the event of fire this protective litter cover is removed, leaving the peat unprotected and open to erosion (Radley 1965).

In management fires, temperatures between 300°C and 500°C, with a maximum of 840°C, have been recorded by Whittaker (1961), which gives some indication of the temperatures that may be experienced in a wildfire. It also shows that *C. vulgaris* seeds in the seedbank may be destroyed, as temperatures that exceed 200°C are lethal. Below 200°C the time of exposure to heat determines how lethal the temperature will be i.e. 120°C for 30 seconds shows a depression of germination, but this response occurs after 20 seconds at 160°C. Germination can be stimulated by a brief exposure (<1 minute) by high temperatures but charring of *C. vulgaris* seeds is lethal even if accompanied by non-lethal temperatures. Charring occurs by direct contact with either flames or smouldering litter (Whittaker and Gimingham, 1962).

Changes to nutrient levels may also have an effect on recolonisation of *C. vulgaris*. Gore and Godfrey (1981) suggest that the infertility of eroding peat is important at preventing natural re-colonisation. Tallis and Yalden (1983) also suggest the extreme infertility and potential mobility of the peat is an obstacle to re-vegetation. However, Legg *et al.* (1992) state that residual peat after a wildfire is adequate for normal shoot growth of *C. vulgaris*, once vegetation established had occurred.

Pollutants, accumulated by dry and wet deposition processes, have also been proposed as reasons for poor regeneration of moorland vegetation in the Peak District National Park (Caporn 1997). The Stalybridge site used within this research is on the boundary of the Peak District National Park and may also be prone to influence from such pollutants. These pollutants include sulphur dioxide (SO_2), nitric oxide (NO) volatile organic compounds (VOCs) and ammonia (NH_3) (Caporn 1997) and they can change the acidity and nutrient composition of the peat, which may affect *C. vulgaris* growth. Yesmin *et al.* (1996) also showed that increased pollution had a detrimental effect on the mycorrhizal fungi within the peat leading to poor growth of *C. vulgaris*. Terry *et al.* (2004) showed, through modelling, that an enhanced nitrogen deposition (greater than 30kg ha year^{-1}) from atmosphere pollution initially increased *C. vulgaris* biomass, but after several decades grasses became dominant. Nitrogen from atmospheric deposition has been reported to increase foliage N content, that predisposes *C. vulgaris* to damage by *Lochmaea suturalis* (heather beetle), frost and drought (Pitcairn *et al.* 1995).

5.2.2 Experimental and natural germination of *C. vulgaris.*

From experimental sowings, Gimingham (1972) showed that germination of *C. vulgaris* seeds could take between eight to fourteen days, with half of the seeds germinating by the end of this period. Seventy percent germinated within six to eight weeks, and 96% had germinated after six months. Gimingham (1972) also reports that *C. vulgaris* seeds can either germinate after seed shedding in the autumn or remain dormant until the following spring. If conditions permit, ungerminated seeds may also enter the seedbank where they may remain viable for many decades (Miller and Cummins 1987). Anderson (2004) suggests that in the northern half of the UK, freshly harvested *C. vulgaris* seeds rarely germinate until 9-12 months after sowing and advocates seed treatment (Geoff Eyre, Hope Valley) to help overcome this. Cold stratification (maintaining the seeds in cold conditions for a period of time to break dormancy) has also been suggested to improve germination rate, however, Mallik and Gimingham (1985) state this has little effect on *C. vulgaris* seeds.

5.2.3 Requirements for germination and establishment of *C. vulgaris.*

Regeneration of *C. vulgaris* on severely burnt moorland does not just depend on the ability of seeds to germinate; the ability of seedlings to become established is also critical.

Plant growth depends on acquisition of essential nutrients of which nine elements (carbon, oxygen, hydrogen, nitrogen, sulphur, phosphorus, calcium, potassium and magnesium) are required in relatively large amounts (macronutrients). Another eight (iron, chlorine, copper, manganese, zinc, molybdenum, boron and nickel) are needed in very small amounts (micronutrients) (Marschner 1995).

Nutrients are obtained through active uptake from the soil and through stomatal gas exchange (Marschner 1991). The ericoid mycorrhizal fungi, *Hymenoscyphus ericae* is usually associated with *C. vulgaris*, and may assist nutrient uptake in the limited nutrient environment of upland moorland. Growth rate has been shown to increase where *C. vulgaris* is inoculated with ericaceous mycorrhizal fungi (Strandberg and

Johansson 1999). There is also some suggestion that seedlings from plants with small, poorly provisioned seed, such as *C. vulgaris,* rely on mycorrhizal fungi to acquire soil nutrients (Allsopp and Stock 1992).

Soil pH influences the availability of nutrients and Marschner (1991) suggests a reduction in soil pH may result in:-

i) an increase in Al and Mn concentration resulting in the development of phytotoxicity,

ii) leaching of Mg, Ca and K from the soil resulting in deficiencies, and/or

iii) changes in rate of decomposition of organic matter and its subsequent mineralization, thereby reducing nutrient availability.

When soil pH is between 4.0 and 4.5 the Al concentration reaches phytotoxic levels for many plants (Marschner 1995). However, plants growing on upland moorland are tolerant of these levels of aluminium. *C. vulgaris* can grow in soils with a pH of 3.0 – 7.0 (Gimingham 1972) whilst Grime *et al* (1996) have suggested that *C. vulgaris* is seldom found in soils with a pH greater than 5.0. In highly acidic organic soils, N mineralisation rates are low and mycorrhizal fungi association may contribute significantly to plant N nutrition (Hartley and Amos 1999).

Light may act as a signal for germination so that, under natural conditions, its perception would indicate that the seed is at or near the soil surface (Ridge, 1999). This is of particular importance for plant species having small seeds with few stored reserves. Where seed germination is inhibited by light, for example, seeds in arid conditions would have a better survival rate if they germinated under the soil thus reducing the risk of desiccation (Ridge, 1999). Failure to germinate in darkness is most commonly observed among small-seeded species, of disturbed habitats and marshland, where many are known to develop abundant and persistent seed reserves in the soil (Grime 1979). These authors further conclude that *C. vulgaris* seeds are inhibited by darkness. *C. vulgaris* seeds also fail to germinate under the canopy of existing plants and favour gap colonisation. Thomas and Vince-Prue (1997) describes how light-sensitive seeds have photoreceptors, a pigment known as phytochrome, which exists in two different inter-convertible forms: Pr, which absorbs red light and Pfr that absorbs far-red light. When a molecule of Pr absorbs a photon of red light it is converted to Pfr which is biologically active and can trigger responses such as seed germination. If a molecule of Pfr absorbs a photon of far-red light it becomes inactive and does not trigger any responses. However Gimingham (1972) suggests that germination can occur, although not as readily, in the dark with favourable fluctuating temperatures (8hr at 30°C and 15hr at 20°C) which may mimic field conditions.

Bannister (1964a) showed that *C. vulgaris* can germinate and seedlings become established over a wide range of soil types and soil moisture regimes. However, germination was increased if the growth medium was 'wet' or above field capacity, i.e. free water was always available suggesting water supply is critical for germination of *C. vulgaris* seeds. Oxygen is important in seed germination, in anaerobic conditions, such as waterlogging, seeds of most plants do not germinate and lose viability (Morinaga, 1926). However, Kinzel (1913) showed that *C. vulgaris* seeds germinate readily in water.

Soil temperatures directly affect microbiological activity and thus organic matter cycling and nutrient availability, in addition to affecting soil water content through evaporation (Marschner 1995). Temperature depends on radiation input but also on the effects of colour, texture, drainage and other soil characteristics (Moore and Chapman 1986).

Low (sub-optimal) or high (supra-optimal) soil temperatures can limit root growth by retarding cell elongation, however, temperature optima vary among plant species (Marschner 1995). Gimingham (1972) stated that the range of temperatures at which *C. vulgaris* seeds will germinate is 17-25°C, however, Grime *et al.* (1996) suggested a wider range of 10-28°C.

C. vulgaris seeds have also been shown to germinate better on a consolidated substrate than a loose one (Gimingham 1960). Seedling establishment is a critical phase in re-establishment of *C. vulgaris* and three factors are considered important, the maintenance of a very moist atmosphere around the seedling for much of the time, a firm seed-bed, so that the young roots are not desiccated in large air-spaces and a seed-bed that is well drained and not waterlogged (Whittaker and Gimingham 1962). Bannister (1964b) also confirmed that *C. vulgaris* will be killed by a protracted period of water-logging.

Suitable sheltered microsites, or safe sites where all environmental requirements for germination and growth are given and where the seed or seedling is protected from extreme environmental conditions, are important for successful seedling establishment on severely burnt heath (Maltby *et al.* 1990, Legg *et al.* 1992).

Above and below-ground competition, for example light, water and nutrients, will effect establishment and growth of *C. vulgaris* seedlings. For example, regeneration of *C. vulgaris* has been show to be limited by the competition for light where grass or litter was too high (Gunnlaugsdottir 1982). *C. vulgaris* is aided by ericoid mycorrhizal fungi in competition for nutrients by enhancing nutrient uptake (Strandberg and Johansson 1999).

Seedling mortality may be attributed to desiccation caused by frost-heave and wind blast (Miller and Cummins (1987), also summer desiccation where *C. vulgaris* plants are not protected by vegetation (Legg *et al.* 1992). Grazing has also been shown to inhibit re-establishment of *C. vulgaris* and has been reported by many authors for example Anderson and Radford (1988), and Tallis and Yalden (1983).

5.3 *RESEARCH AIMS.*

The results of the surveys of Darwen Moor (Chapter 4), Stalybridge (Appendix 1) and other reports from moorland post wildfire (for example Maltby *et al.* 1990) show that re-colonisation of moorland by *C. vulgaris* is very slow. If natural and/or post-fire management are to achieve regeneration of these degraded sites then *C. vulgaris* seeds must have the capability of germinating and growing in the residual peat. Within this context, the research aim of this chapter was to record germination and growth of *C. vulgaris* on peat samples from a moor post-wildfire, using a bioassay under controlled conditions, within a growth cabinet.

Bioassays measure plant response and provide information on biological activity of the whole organism and are widely used in plant growth experiments. Rorison (1967) used this approach to examine vegetation growth on soil from a wide range of geological strata. Other examples of research using bioassays are given by Fenn *et al,* (2006) who used bioassays to show plant growth on forest soils with enhanced fertilisation and Troelstra *et al* (2001) who studied plant responses to soil pathogens. A bioassay was selected within this investigate to evaluate germination and growth potential of *C. vulgaris* in preference to chemical analysis of the peat. Knowledge of the nutrient availability and/or potential peat toxicity may not have shown the ability of *C. vulgaris* to grow in peat derived from moorland post-wildfire.

A growth cabinet was used so that environmental conditions such as temperature, water, light and photoperiod could be controlled. Using controlled conditions ensured results would show germination and growth of *C. vulgaris* in relationship to peat properties and not from other variable environmental conditions.

5.4 *MATERIALS AND METHODS.*

5.4.1 Growth cabinet.

A growth cabinet was designed and constructed to give optimum conditions for germination and growth of *C. vulgaris* (see Figure 5.0). This was based on commercial growth cabinet designs and advice from horticultural suppliers (Kays Horticultural Products, Whitehaven).

Light was provided by a horticultural Mercury 'growlight' system with a Philips 500-watt bulb (Kays Horticultural Products, Whitehaven). A Photoperiod of 12/12hrs (light/dark) was provided throughout the whole experimental period (26 weeks). The duration of experimental period was chosen as Gimingham (1972) states that 95% of *C. vulgaris* seeds germinate within six months.

Heating was provided by an under-soil-heating cable (Parasene 12m, H & E Knowles Ltd, Cradley Heath) within 10cm of damp horticultural sharp sand on the base of the cabinet. Temperature of the damp peat samples was maintained at approximately 14°C min, 18°C max by the use of a thermostat on the under-soil-heating cable. Air temperature directly under the lamp was 16°C min, 18°C max.

Water (1-2cm deep) was supplied in troughs above the sand in which the seed-trays stood. Trays were always in contact with the water in the troughs, which ensured peat samples remained at or above field capacity. Water was replenished as required. To ensure that the peat surface did not dry out, samples were also sprayed at 12 hr intervals for approximately two minutes with a handheld pump water sprayer (Hozelock, Aylesbury). Deionised water was used in all methods of watering to prevent supplementary minerals affecting growth.

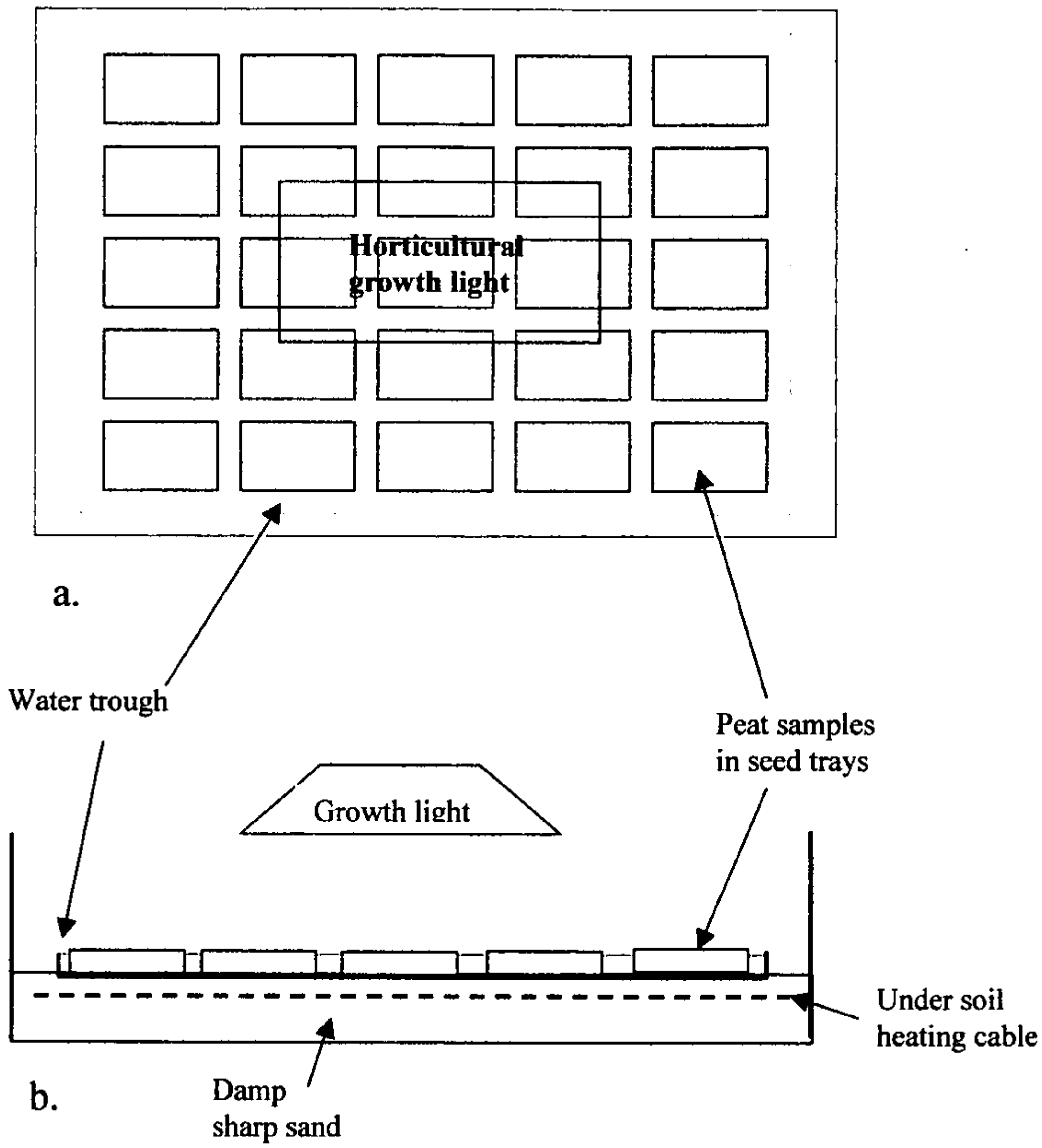


Figure 5.0 Growth cabinet for maintenance of optimum germination and growth conditions for *C. vulgaris*. (Size 1.72m wide x 1.2m deep x 1.0m high (a) plan view (b) side elevation, not drawn to scale).

5.4.2 *C. vulgaris* seed preparation.

Seed capsules were collected by hand from *C. vulgaris* bushes adjacent to the Stalybridge research site (Nat. Grid: SE000019) one week before experimental set-up (October 2001). These were allowed to air dry at approximately 20°C. Seeds were extracted from the capsules just prior to experimental set-up by placing the litter (small pieces of *C. vulgaris* plants and capsules) in a large (30 x 45cm) plastic bag and shaking vigorously (one minute). Litter and extracted seeds were dry sieved (1.5mm mesh size) to remove large pieces of litter.

5.4.3 Preparation of growth medium.

Peat was collected from locations determined by application of random numbers from an unvegetated, burnt section of the Stalybridge research site. Two types of peat were collected, i) hard surface crust which had been exposed to the rain, wind and sun, (as discussed by Maltby *et al.* 1990) and ii) peat from just under this crust. This moorland peat and a commercial ericaceous compost (B&Q, Eastleigh) were each placed in a 'half seed-tray' (17 x 23cm) (N. A. Kays Horticultural Products, Whitehaven) and treatment applied as follows: -

a. Crust maintained in one piece, seeded.
b. Manipulated crust (broken into small pieces by hand, 0-10mm), seeded.
c. Sub-crust peat (collected from under crust), seeded.
d. Commercial ericaceous compost– seeded.
e. Manipulated crust (broken into small pieces by hand, 0-10mm) un-seeded.

Seeded treatments (a – d) received 0.5g of *C. vulgaris* seeds and litter (section 5.2.2) with a minimum of 50 seeds, counted in each sample (weight sample of seeds was placed on a white piece of paper, examined and counted with the aid of a hand lens (x5)).

Samples d and e were set up to act as controls:-

d) To measure viability of the *C. vulgaris* seed a commercial ericaceous compost was chosen because it that provided all required nutrients for *C. vulgaris* growth for six months (B&Q, Eastleigh)

e) To measure potential germination from the seedbank. Seeds germinating from the seedbank (in a-c) may have potentially added to those used experimentally.

All peat samples were 3 - 5cm deep. Five replicates of each treatment were placed in a growth cabinet. No growth of plants was observed before the start of the experiment. Seed trays were randomly repositioned (by reference to random numbers) every five days to eliminate any potential effects of environmental gradients within the growth cabinet.

Germinated seedlings were counted after a period of 12 weeks. Only seedlings with at least the first two leaves (plus cotyledons) open were included in the count. At 26 weeks (termination of experimental period in controlled environment) seedlings were recounted. The percentage of *C. vulgaris* seedlings growing at 12 weeks compared with final count was calculated for each treatment. Seedlings that died within this 26 week period were also counted.

5.4.4 Statistical analysis.

A mixed ANOVA with repeated measures using the SPSS statistical package (Version 10.0) was used to test differences between sample times and between peat treatments.

Within-subjects: - sample time, means were compared with a t-test using Bonferroni adjustments (Kerr *et al.*, 2002).

Between subjects: - peat type, data were Log_{10} transformed to obtain homogeneity of variance (Zar, 1974).

5.5 *RESULTS.*

5.5.1 Statistical analysis.

The assumption of sphericity in univariate repeated-measures ANOVA was overcome by using the Greenhouse-Geisser adjusted P value (Kerr *et al.*, 2002). The results of the 'within-subject effects' of the mixed ANOVA show there is a significant difference in *C. vulgaris* seedling count at all times of sampling, (12 and 24 weeks), $F(2,32) = 39.244$ ($P<0.01$), *t*-test with Bonferroni corrections = $P<0.05$ in all tests.

The 'between subject effects' tests show there is no significant difference between the *C. vulgaris* seedling count on the various peat treatments.

The manipulated peat (unseeded) used as a control (treatment e) to detect growth of *C. vulgaris* from the peat seedbank, was not included in the statistical analysis, as tests were to show growth from known seeds.

5.5.2 Germination and growth of *C. vulgaris* seeds.

No germination of *C. vulgaris* was recorded on the unseeded control (treatment e).

Germination and growth of *C. vulgaris* seeds at twelve weeks occurred on all types of seeded moorland peat, and the seeded commercial ericaceous compost. Mean numbers of *C. vulgaris* seedlings recorded for crust (a), manipulated crust (b), and sub-crust (c) were 9, 5 and 5 respectively. Ericaceous compost (d) had the highest mean count of 10.

Established seedling numbers at 24 weeks followed the same pattern on the moorland peat:- crust (a) 47, manipulated crust (b) 41 and sub-crust (c) 35. However, number of seedlings on the Ericaceous compost was the lowest with 21 seedlings, all counts were mean (Figure 5.1).

No seedling mortality was recorded on any peat treatment.

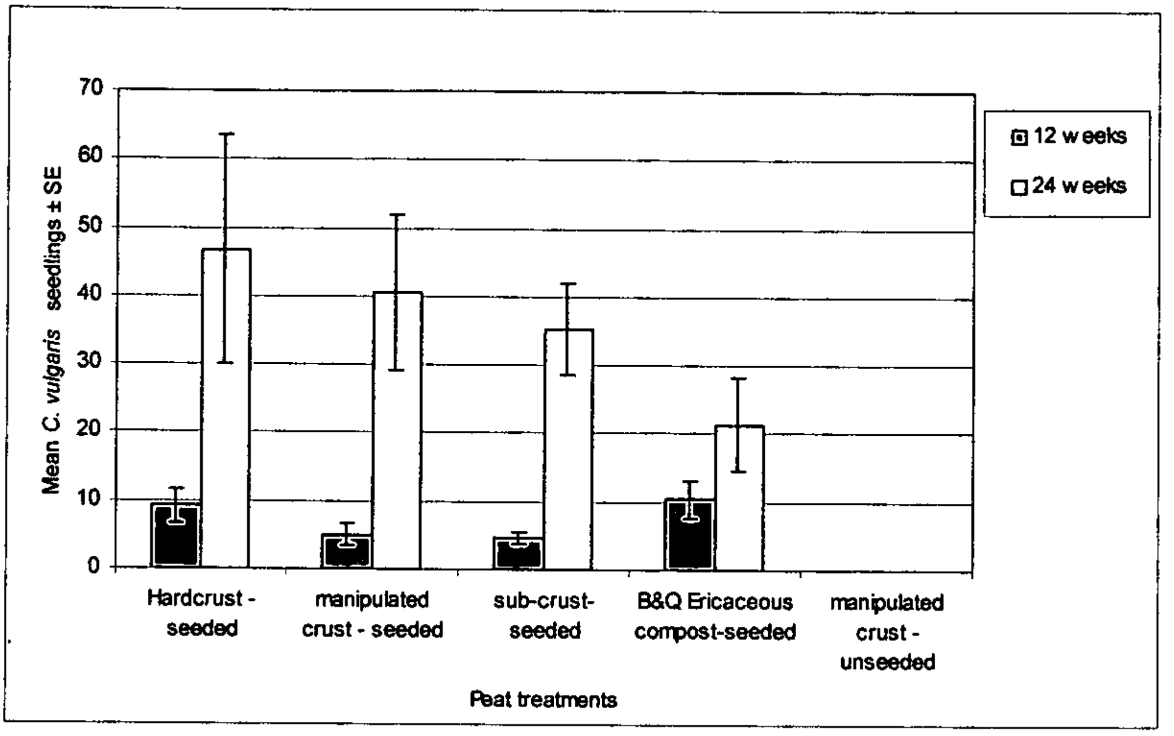


Figure 5.1. Number of *C. vulgaris* seedlings on various treatments of moorland peat, post-wildfire, at 12 and 26 weeks after sowing (Data mean ± SE, n=5).

5.5.3 Percentage of germinated *C. vulgaris* seeds at twelve weeks.

Of the total *C. vulgaris* seedlings recorded at 24 weeks on the crust, manipulated crust and sub-crust 20, 12, and 13% respectively, were growing at 12 weeks, (Figure 5.2).

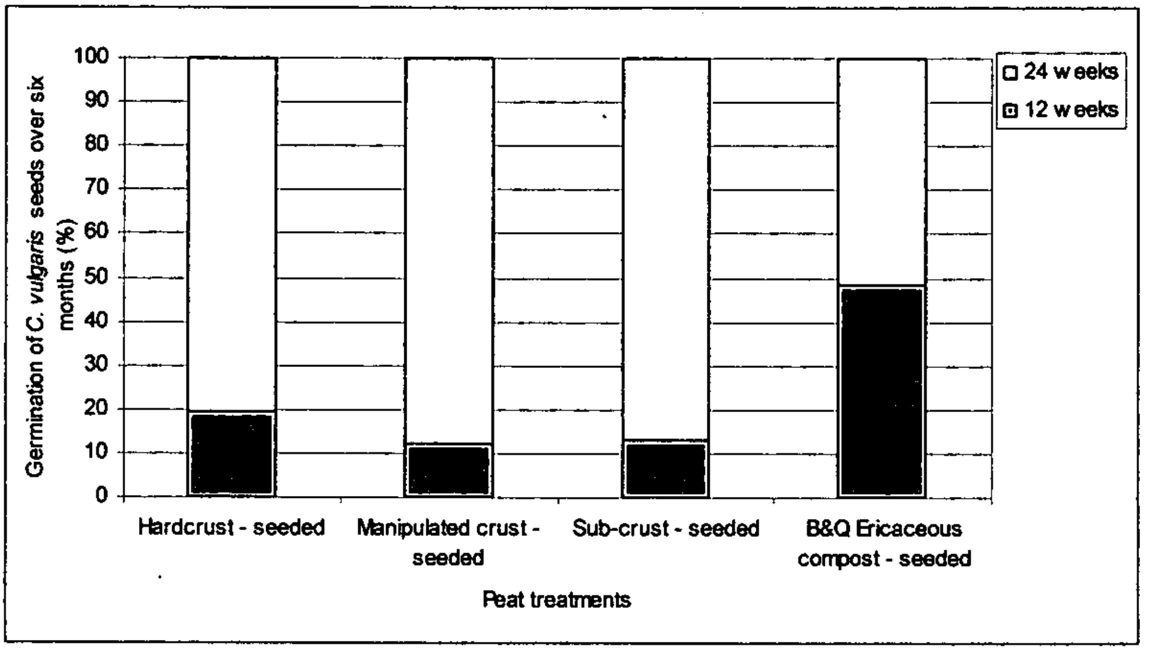


Figure 5.2. Percentage of germinated *C. vulgaris* seeds grown on moorland peat, post-wildfire at 12 and 26 weeks after sowing.

5.6 *DISCUSSION.*

Germination and growth of *C. vulgaris* was recorded on all sown peat treatments under controlled conditions. This indicates that properties of the peat from the Stalybridge research site, post-wildfire, were not the limiting factor in the regeneration of this site. Legg *et al.* (1992) also found that untreated surface crust did not hinder germination of *C. vulgaris* under greenhouse conditions.

A hard crust forming on the bare peat has been cited as a reason for poor recolonisation of *C. vulgaris* by modifying the physical properties of the surface, particularly reducing water penetration (Gimingham 1972, Mallik *et al.* 1984). In this study, however, recorded *C. vulgaris* growth on the hard crust was not significantly different from the other peat treatments. Also, seedling establishment on all the peat treatments occurred without any recorded death. This suggests that mechanical impedance of the peat did not inhibit seed radicle penetration into the peat. Mechanical impedance has also been shown to increase as soil dries (Marschner 1995), which did not occur under controlled conditions. Therefore, if the environmental conditions of the peat, in terms of moisture and temperature, could be enhanced then the physical properties of the peat would not hinder germination and growth of *C. vulgaris* seeds.

As germination and growth of *C. vulgaris* continued for the whole of the experimental period (26 weeks) in controlled conditions, it is suggested that the nutrient status of the peat is adequate for continued growth of *C. vulgaris* on the Stalybridge research site. However, this does not agree with findings from Gore and Godrey (1981) who cite poor nutrient status of bare peat after a wildfire as a reason for poor natural re-colonisation. It is also suggested that the pH of the moorland peat samples in this investigation did not influence germination and growth and therefore nutrient uptake by the plants. A pH of 3.7 had been recorded on this site (chapter 2 and appendix 1), which is within the most commonly found growth range of *C. vulgaris* of 3.5 to 6.5, (Gimingham 1972) and higher than pH 3.2 under which germination diminishes considerably (Helsper and Klerken 1984).

Deposition from air pollution has also been suggested as a cause of poor regeneration of *C. vulgaris* (Yesmin *et al.* 1996, Caporn 1997). The peat in this investigation was from the Stalybridge site; east of the industrial city of Manchester, with a westerly prevailing wind any deposition of air pollution may have reduced germination and growth of *C. vulgaris*. A significant difference was not recorded betweèn germination and growth of *C. vulgaris* on the moorland peat compared to the commercial peat, therefore it is suggested there was no effect from pollutants or toxins. However, there has been much erosion of peat from this site and any toxins from industrial pollution or from the wildfire may have been removed, also the deposition of pollutants has fallen significantly since 1970 (Dore *et al.* 2006).

Two controls were used within this experiment. The first was to demonstrate whether any viable *C. vulgaris* seeds were present in the peat samples. This would have had the potential to increase the number of *C. vulgaris* seedling recorded on the peat treatments. However, no germination of *C. vulgaris* was recorded in the control treatments, which suggests the seedbank was removed in the wildfire and/or subsequent years. The result may also show that seeds are not being dispersed into the site from surrounding *C. vulgaris*. If seeds were present they may be nonviable or dormant for the period of this investigation. The spread and quantity of *C. vulgaris* seed-rain into this site and the viability of seeds will be investigated in Chapters 6 and 7.

The second control was to test viability of *C. vulgaris* seeds used in this investigation, with good viability being recorded. Germination on the commercial compost, within the first 12 weeks, was the highest (48%), but not significantly different from the other peat types. After 26 weeks the seedling count was the lowest (Figure 5.1) and again not significantly different from the moorland peat treatments. This may suggest properties of the commercial compost that enhanced early germination, such as an increased contact between seed and compost that may have increased imbibition and provided a more suitable or stable temperature. Mycorrhizal fungi may have been present within the peat; this has been shown to increase germination of seeds in some plant species (Zettler and Hofer 1998) and to increase the biomass of *C. vulgaris* seedlings (Dietz and Steinlein 1996). However, this aspect was not investigated further in this research.

One factor that was not investigated in this study was the possibility that the commercial compost may have already contained *C. vulgaris* seeds. This could have easily been investigated by having another control: a commercial ericaceous compost treatment that was not seeded with *C. vulgaris* seeds. However, the results showed that after 26 weeks the ericaceous compost had the lowest count of seedlings, therefore it must be assumed that if any residual *C. vulgaris* seeds germinated they did not influence the results substantially. Also, this was only a control to investigate viability of *C. vulgaris* seeds if seeds did not germinate on the moorland peat samples, which was not the case.

Gimingham (1972) suggested that 70% of *C. vulgaris* seeds would germinate within six to eight weeks and 95% within six months; whilst Grime *et al.* al (1981) suggests 88%. However, such proportiôns of germinated *C. vulgaris* seeds were not found on the peat samples within this investigation. At twelve weeks the highest was 20% (hard crust) of total count of *C. vulgaris* seeds germinated on that treatment. Even germination on the commercial compost (48%) at twelve weeks did not approach the results of Gimingham (1972). Legg *et al.* (1992), in a similar experiment, also found the germination rate of *C. vulgaris* seed on surface crust under greenhouse conditions to be lower than those expected from literature. Many factors may account for this inconsistency; experimental design, age of *C. vulgaris* seed, growth medium used by Gimingham (1972) and the properties of the peat and/or treatments used in this experiment. However, *C. vulgaris* seeds used in this experiment were fresh and the growth conditions were optimal and as given in the appropriate literature (see section 5.2.3). This may have suggested that properties of peat post-wildfire were inhibiting germination of *C. vulgaris* seeds, however, the count of *C. vulgaris* seedlings on the commercial peat contradict this, with only 48% of total germinated seeds growing after twelve weeks.

Some seeds within this investigation may have become dormant and might germinate much later as suggested by Gimingham (1972) and Anderson (2004). However, they had received optimum conditions for 26 weeks, which may be longer than the time received on upland moorland, as will be investigated in Chapter 6.

Although this investigation only used peat from one site, the results suggest that peat from a degraded site post-wildfire may support germination and growth of *C. vulgaris* without any additional nutrients, lime or surface manipulation, if optimum growth conditions were provided. However, to replicate these optimum growth conditions in upland moorland would necessitate a high cost in materials and labour. Contemporary moorland management for the reinstatement of *C. vulgaris* does supply some of the germination and growth requirements in the practice of using nurse plant species, geotextiles and heather shoots to provide peat stability and 'safe-sites'.

In conclusion, results from this experiment suggest that the physical or chemical properties of peat post-wildfire, when environmental conditions are adequate, do not inhibit germination or growth of *C. vulgaris.* The environmental conditions of upland moorland, which had been eliminated from this study, will be investigated in chapter 6.

6.0 CHAPTER 6

ENVIRONMENTAL CONDITIONS OF UNVEGETATED PEAT POST-WILDFIRE AND GERMINATION POTENTIAL OF *C. VULGARIS* SEED IN DROUGHT AND ENHANCED CONDITIONS.

6.1 INTRODUCTION.

Results from chapter 5 suggest the environmental conditions of upland moorland were hindering the re-colonisation of *C. vulgaris* on bare peat post-wildfire. This chapter investigates a selection of these environmental conditions and their effects on germination and growth of *C. vulgaris* seed.

6.2 *BACKGROUND TO THIS STUDY.*

The environmental conditions of growth media are crucial to determine the regeneration of vegetation (Harper 1977); however, conditions that occur within bare peat following wildfire have received little attention. Peat exposed to the atmosphere quickly dries out and is slow to absorb water (i.e. becomes hydrophobic). This is very detrimental to plant growth and has implications for hydrological and geomorphological processes, including reduced infiltration capacity of soils, increased overland flow and soil erosion (Doerr *et al.* 2000); all of which can be seen at the Stalybridge site (Section 2.4). Fire has also been shown to increase water repellence of soils (DeBano 2000).

Soils receive both long and shortwave radiation that is absorbed, reflected and re-radiated, with dark soils such as peat, receiving more energy than the reflective light coloured soils. Daily maximum and night minimum temperatures and the evaporation rate are also higher, with dark soils having the most extreme environmental conditions (Bannister 1976).

Climatic conditions may also have a great influence on the properties of peat within a moorland setting and may affect the success of post-fire management. Data from the Climate Change Scenarios for the UK (Hulme and Jenkins 1998) suggest that for the medium-high UK Climate Impacts Programme (UKCIP) 1998 scenario (with respect to the 1961-90 mean), the annual precipitation for 2080 will increase by 8% for the area close to the research sites. However, summer precipitation (2080) for the same area is predicted to decrease by 13%. Annual mean temperature for the same period is expected to increase by 2.7°C (Hulme and Jenkins 1998). This prediction of warmer, drier summers and wetter winters may also have an effect on germination and growth of vegetation from post-wildfire management and natural regeneration.

The optimum germination requirements for *C. vulgaris* seeds are temperature 10-28°C and soil water at field capacity (section 5.2.3). These germination requirements were also discussed by Pons (1989) who stated that *C. vulgaris* seeds cannot germinate in dry conditions. However, *C. vulgaris* seeds may survive imbibition and drying out in the first 12hr of imbibition as suggested by Opik and Simon (1963). These optimum requirements are not absolute and may change under different conditions, for example optimum temperature for photosynthesis is raised as light intensity increases (Bannister 1976). Microsites or safe-sites are also important and seedling establishment is enhanced by any factor that reduces drought stress and increases nutrient uptake (del Moral and Bliss, 1993). However, recruitment in plant populations may be limited by the availability of microsites or by the availability of seed (Eriksson and Ehrlen 1992).

C. vulgaris seeds landing on bare peat may remain there, be removed by wind or water, become buried or predated. Although susceptibility to predation is usually associated with large seeds *C. vulgaris* seeds have been shown to be removed from the seedbank by ants (Brian *et al.* 1965). Germination may occur immediately after dispersal, as demonstrated in chapter 5, or in the spring of the following year (Gimingham 1972) seeds may also persist in the soil (Putwain and Gillham 1990). Persistent seeds may become dormant until conditions are appropriate for germination although death can occur at any time (Clark and Wilson 2003). The mortality rate of C. *vulgaris* seeds is very low if buried, although germination time has been shown to increase with burial time (Pons, 1991).

6.2.1 Seed dormancy.

Even when external conditions are favourable (sufficient water, oxygen, light and temperature) some seeds will fail to germinate and such seeds are said to be dormant. Seed dormancy aids survival from time of seed dispersal to time of germination and ensures continuance of plant generations.

Using Baskin and Baskin's (1998 and 2004) classification of dormancy, there are five main dormancy types:-

i. Physiological – germination is prevented by a mechanism with the seed embryo or covering structure, seeds often need periods of light or cold or warmth to break dormancy.
ii. Morphological – seed embryo is underdeveloped or not fully formed at seed dispersal.
iii. Morphophysiological - occurs in seeds with underdeveloped embryos that also have physiological dormancy.
iv. Physical – Seed or fruit coat is resistant to water uptake, which prevents germination.
v. Combinational – occurs in seeds that have a combination of impermeable seed or fruit coat and physiologically dormant embryos.

Methods used to enhance germination and growth of *C. vulgaris* in moorland management includes protection of the seeds with geojute, brash and cut heather shoots used as a seed source and protection. Chemical treatments and smoking *C. vulgaris* seeds to break dormancy have also been attempted and have been shown to be successful (Thomas and Davies 2002, Anderson 2004). Cold stratification, (chilling seeds) is often suggested as a method to break seed dormancy, however Mallik and Gimingham (1985) suggest it has little effect upon germination rate of *C. vulgaris.*

6.2.2 Improving germination and growth conditions.

In landscape design and in agriculture a method used to promote growth conditions is incorporation of water-retaining polymers. These polymers can be either natural or synthetic. Natural polymers are starch-based, commonly derived from grain crops and used in the food industry as thickening agents (Mikkelsen 1994). Two types of polymer used in agriculture are classified as linear acrylamide/acrylate and cross-linked polyacrylamide/polyacrylate, depending on their molecular structure.

Linear acrylamide polymers dissolve in water and are very effective at controlling soil erosion in irrigation projects in arid and mediterranean climates of the world (Green and Stott, 2001). They bind soil particles resulting in particles too large to remain suspended and consequently settle out in the irrigation furrow.

Cross-linked polyacrylamide is a granular crystal and has the ability to attract water because of its molecular structure. Water does not dissolve the polymer but is absorbed into the network of spaces created by its cross-linked structure. Cross-linked polyacrylamide polymers may absorb 400 times their weight in water and obtain the consistency of a gel (Huttermann *et al.* 1999, Yangyuoru *et al.* 2006).

Cross-linked polyacrylamides, sold commercially are non-ecotoxic, moderately degradable (Bayer CropScience Ltd. 2006) and suitable for use in gardens, houseplants and landscaping to increase the soil water-holding capacity and decrease watering frequency. Such materials have been available since the 1950's and have been in and out a favour for agricultural and horticultural use. There is some concern about the claims made by manufacturers about polymers and their safety in the environment. Acute toxicity is reported as:- Oral LD50 (rat)>5000mg/Kg and dermal LD50 (rat)>2000mg/Kg and pH 6.0-8.0 (aqueous solution) (Bayer CropScience Ltd. 2006). The World Health Organisation (WHO, 2003) showed that acrylamide has been found in drinking water and food and may be implicated in cancer.

Research has also considered claims that water held in the gel is not available for plant uptake, toxicity of degrading gels may cause environmental problem and their effectiveness at increasing germination and growth of plants species is uncertain. However, water held in the gel has been shown to be available for plant uptake although the wetting/drying cycles reduce absorbency (Green *et al.* 2004). Water retention in sandy soils is increased with the addition of gels, which limit deep percolation losses of water (Al-Darby 1996) although they gradually fail over time with respect to capacity uptake and retention of water (Holliman *et al.* 2004). When used in soils under irrigation systems, gels decreased runoff by 50-70%, with reduced erosion (Levy *et al.* 1991). Holliman *et al.* (2004) suggests polyacrylamide gels are safe as they only release acrylamide into the environment when they are exposed to temperatures over 35° C). Gels have been shown to inhibit germination of seeds, Henderson and Hensley (1987) found seeds from *Robinia psuedoacacia* (black locust), *Gleditsia triacanthos* (common honeylocust and *Gymnocladus diocia* (Kentucky coffeetree) were all negatively affected by a gel coating. Lettuce seed also had a reduced germination rate when gels were used at a high concentration (Woodhouse and Johnson 1991). However, gels have a great potential to benefit site regeneration schemes where soils is left exposed, here gels have been shown to increase infiltration, reduce soil surface hardening and erosion, by both rainfall and overland flow (Vacher *et al.* 2003).

6.3 *RESEARCH AIMS.*

The aim of this chapter is to record environmental conditions that prevail on bare burnt moorland over a prolonged period in terms of temperature and water content of the peat (section 6.4). To investigate germination of *C. vulgaris* seeds in drought conditions (section 6.5) and to evaluate the use of polyacrylamide gel as an aid to providing enhanced germination and growth conditions for the sowing of nurse species (section 6.6). Each section has its own methodology and results; these are followed by a chapter discussion.

6.4 *SELECTED ENVIRONMENTAL CONDITIONS OF PEAT ON THE STALYBRIDGE RESEARCH SITE.*

6.4.1 Materials and methods.

To measure the water content and temperature of the bare peat post-wildfire within a moorland setting a datalogger (Datahog 2, Skye Instruments, Llandrindod Wells, Wales) was installed on the Stalybridge site (November 2003). This was in a deep peat section of the Environmental Sensitive Area (ESA) that had remained bare since the 1980 fire. The datalogger was set-up to record readings from six sensors (three temperature, three water content) at 30-minute intervals. The data were downloaded every eight to ten weeks on to a computer laptop using SkyeLynx Standard Edition Programme (Skye Instruments). The datalogger and all wires and sensors were buried for security with sensors within the top 2cm of peat. The manufacturer (Skye Instruments) performed calibration of the datalogger; *in situ* calibration was not required. Output data were calculated to give the mean of the three sensors (temperature and water content).

Although this method of data collection showed the environmental conditions of the bare peat post-wildfire it did not measure the climate of microsites. Data collected was compared to optimum germination and growth conditions for *C. vulgaris* published in literature (Gimingham 1972, Grime *et al.* 1996) whilst accepting these optimum conditions are not necessarily absolute conditions (Bannister 1976).

6.4.2 Calculation of field capacity.

Prior to installation, the datalogger was used to establish the field capacity of the peat from the Stalybridge site. Peat was placed in deep trays 11 x 7 x 10cm deep (n=3) with drainage holes in the base, a water content sensor was inserted in each tray (top 2cm) and the peat tampered down to make good contact with sensors. Peat trays were inserted in a tray of water to the depth of peat (8cm) and left for seven days so that the peat was fully saturated. The datalogger was set to record water content of peat every five minutes. Peat trays were removed from the water and allowed to drain, with data noted when water content readings remained constant. This was repeated three times giving a total of nine readings from which the mean water content (field capacity) was calculated. This method was similar to that described by Moore and Chapman (1986), but data were collected by the datalogger. This method also ensured both peat samples (*in situ* and laboratory) received similar treatment prior to data collection; the peat was disturbed for the placement of sensors.

6.4.3 Results from environmental conditions of peat.

The datalogger recorded temperature and water content of the bare peat for 17 months, and was removed from site at the beginning of May 2005 due to necessity brought about by site management. Missing data occurred from 12th April – 18th May 2004 due to loss of battery power.

From samples, the field capacity of peat from the Stalybridge site was calculated and expressed as a volumetric measurement 0.27 Ø (m^3/m^3), this figure was used to show when optimum water content for germination of *C. vulgaris* seeds was reached.

Only within three months (July, August and September 2004), during monitoring, did the temperature and water content (field capacity) meet the optimum requirements for germination of *C. vulgaris* seeds and for the required germination period (15 days) (Table 6.0).

Field capacity was attained in all of the months during the rest of the monitoring period. This ranged from 5.2 days (March 2005) to 30 days (November 2004), although, these were not necessarily consecutive days (Table 6.0).

Table 6.0 Periods during monitoring when datalogger recorded temperature and water content of the peat that met optimum conditions for germination of *C. vulgaris* seeds. (Months when optimum conditions were attained)
(* Incomplete data sets for these months from 12th April to 18th May 2004).

	Time when optimum water content and temperature of peat were met.		Time when optimum water content of peat was met.	
	Hours	Days	Hours	Days
Dec 03	0	0	630.5	26.3
Jan 04	0	0	666.0	27.8
Feb 04	10.0	0.42	431.5	18.0
Mar 04	0	0	173.0	7.2
April 04*	0	0	107.5	4.4
May 04*	0	0	0	0
June 04	98.5	4.1	134.5	5.6
Jul 04	547.5	22.8	576.0	24.0
Aug 04	446.5	18.6	458.5	19.1
Sept 04	360.5	15.0	479.5	20.0
Oct 04	120.5	5.0	450.0	18.8
Nov 04	5.0	0.3	720.5	30.0
Dec 04	0	0	682.5	28.4
Jan 05	0	0	670.0	27.9
Feb 05	0	0	451.5	18.8
Mar 05	0	0	124.5	5.2
April 05	0	0	168.5	7.0

The main seasonal and diurnal fluctuation in data recorded were:-

1. Large diurnal fluctuation in temperature during summer months, for example Figure 6.0, where high peaks show daily changes.

2. Little diurnal change in temperature during winter months, Figure 6.1, represented by small peaks.

3. High sharp peaks showing fluctuations of water content of peat in most months (for example Figure 6.0 and 6.1).

4. Very low water content of the peat in the latter part of the month (February 2004), when water held as ice and not recorded on the datalogger (Figure 6.1).

5. Higher water content recorded in winter than in summer months (Figure 6.0 and 6.1).

6. Temperature exceeded 28°C (Maximum germination temperature) for a number of days in August 2004 (Figure 6.0)

The mean of the three sensors (water content and temperature) in addition to limits of germination were displayed graphically. Four examples of these are shown in Fig 6.0 (Summer) and Figure 6.1 (Winter). Full data sets are provided in Appendix 6.

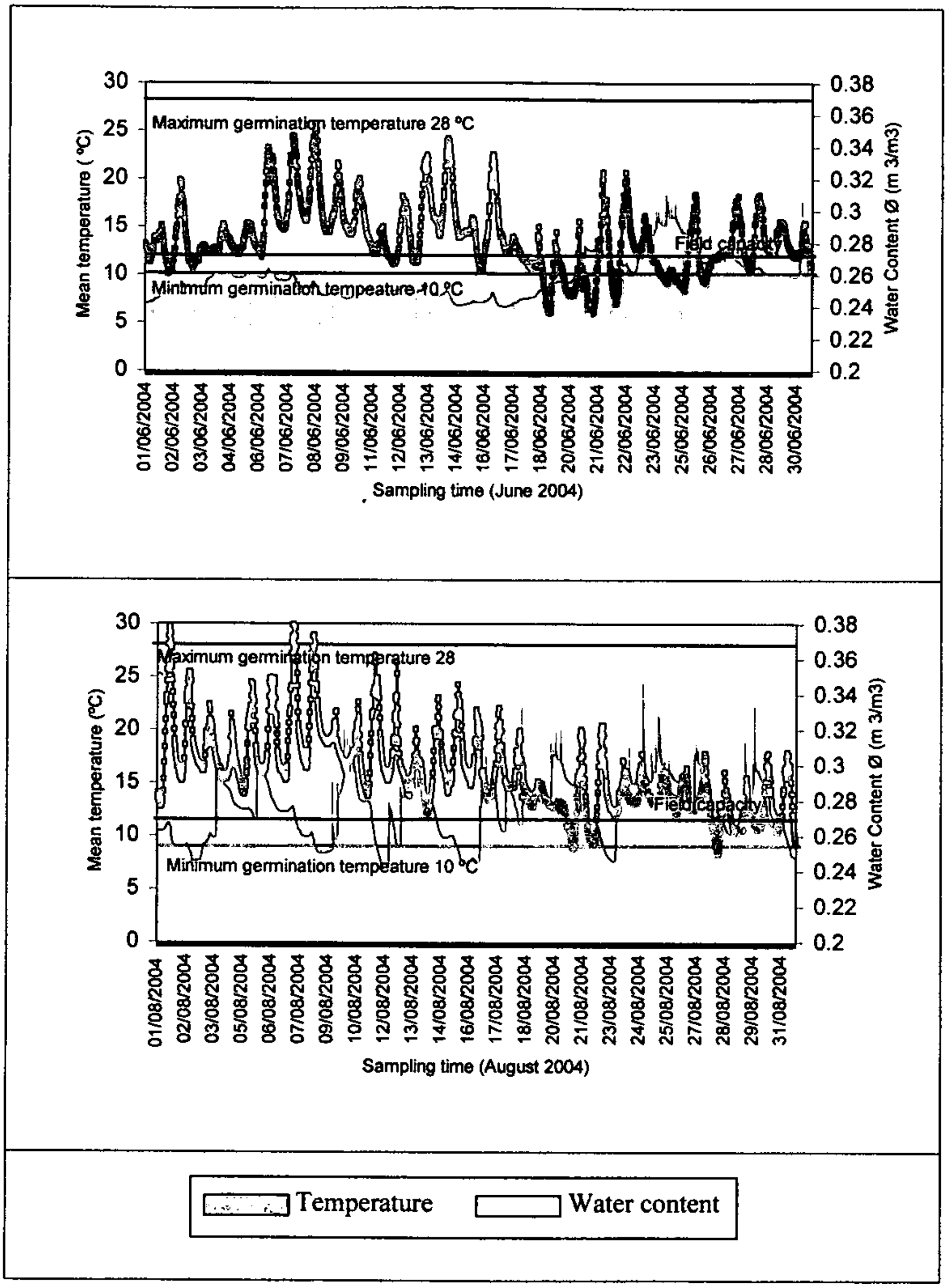


Figure 6.0 Datalogger results for June and August 2004 of water content (blue) and temperature (red) of bare peat on the Stalybridge research site. Optimum germination conditions of *C. vulgaris* seeds are also shown. (Data mean, n=3).

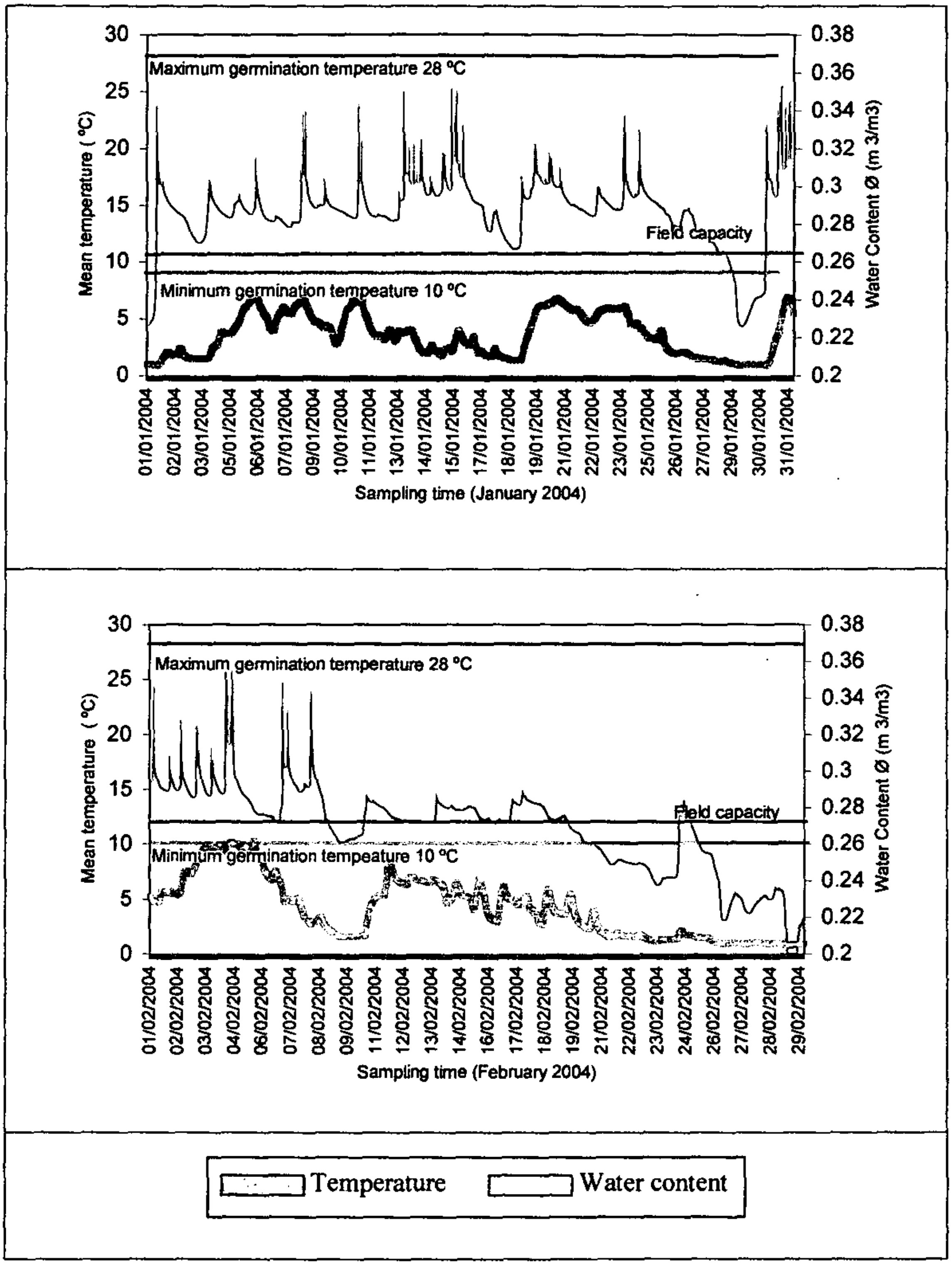


Figure 6.1 Datalogger results for January and Febrary 2004 of water content (blue) and temperature (red) of bare peat on the Stalybridge research site. Optimum germination conditions of *C. vulgaris* seeds are also shown. (Data mean, n=3).

6.5 *GERMINATION OF CALLUNA VULGARIS SEEDS SUBJECTED TO DROUGHT CONDITIONS.*

Two experiments were used to explore how drought conditions might affect germination of *C. vulgaris* seeds. In all experiments fresh *C. vulgaris* seeds were collected by hand, air dried and sieved to remove large pieces of litter as described in section 5.4.2. Water used in all experiments was distilled and deionised.

6.5.1 Experiment 1.

Small plant pots (6cm x 6cm x 7cm deep) were filled with air-dried ericaceous compost (B&Q). The pots (n=78) were placed in a growth cabinet with half standing in water-filled trays and sprayed daily (wet treatment) (see section 5.4.1); the remainder stood in dry trays and were not watered (dry treatment). All pots received 12/12 hrs of light/dark and heat from an under soil warming cable, as in section 5.4.1. Pots remained under this regime for seven days to acclimatise to the environmental conditions and to allow the peat in pots, standing in water, to become fully saturated.

On day eight *C. vulgaris* seeds (n=5) were spread, by hand, on each pot. Three pots (control) from the 'wet' pots and three from the 'dry' pots were removed at random (using random number tables) and placed in controlled conditions, (12/12 hrs light/dark, warmth and were watered from below and by spraying as in section 5.4.1). The remaining pots remained in the growth cabinet and received the same conditions (light and heat) except all watering from below and spraying were withheld.

Every five days, until 60 days, three pots from the 'wet' and three from the 'dry' treatments were randomly selected and removed, marked for identification, and placed in the controlled conditions. Numbers of germinated *C. vulgaris* seeds were counted every five days starting at day 15. Pots were also moved randomly every five days within the growth cabinet to eliminate any environmental conditions having an effect on germination (Bertero *et al.* 1999, Lake and Hughes 1999). All *C. vulgaris* seedlings were counted but not removed, as disturbance of the peat surface may have buried other seeds and delayed germination. Once reached, all pots remained in the controlled conditions for 55 days; seedlings were counted when two true leaves were identified.

6.5.1.1 Statistical analysis.

Data were first tested for homogeneity of variance (Levene's test). A Mann-Whitney test was performed using the statistical package SPSS (Version 10.0) to test difference between seeds grown in wet and dry peat.

6.5.2 Results of experiment 1.

Significantly more *C. vulgaris* seeds germinated on wet growth medium than the dry peat ($P < 0.05$).

C. vulgaris seeds germinated on all 'wet' treatments irrespective of time kept under drought conditions; whereas germination on 'dry' treatments only occurred on three (control, 5 and 20 days in dry conditions) (Figure 6.2).

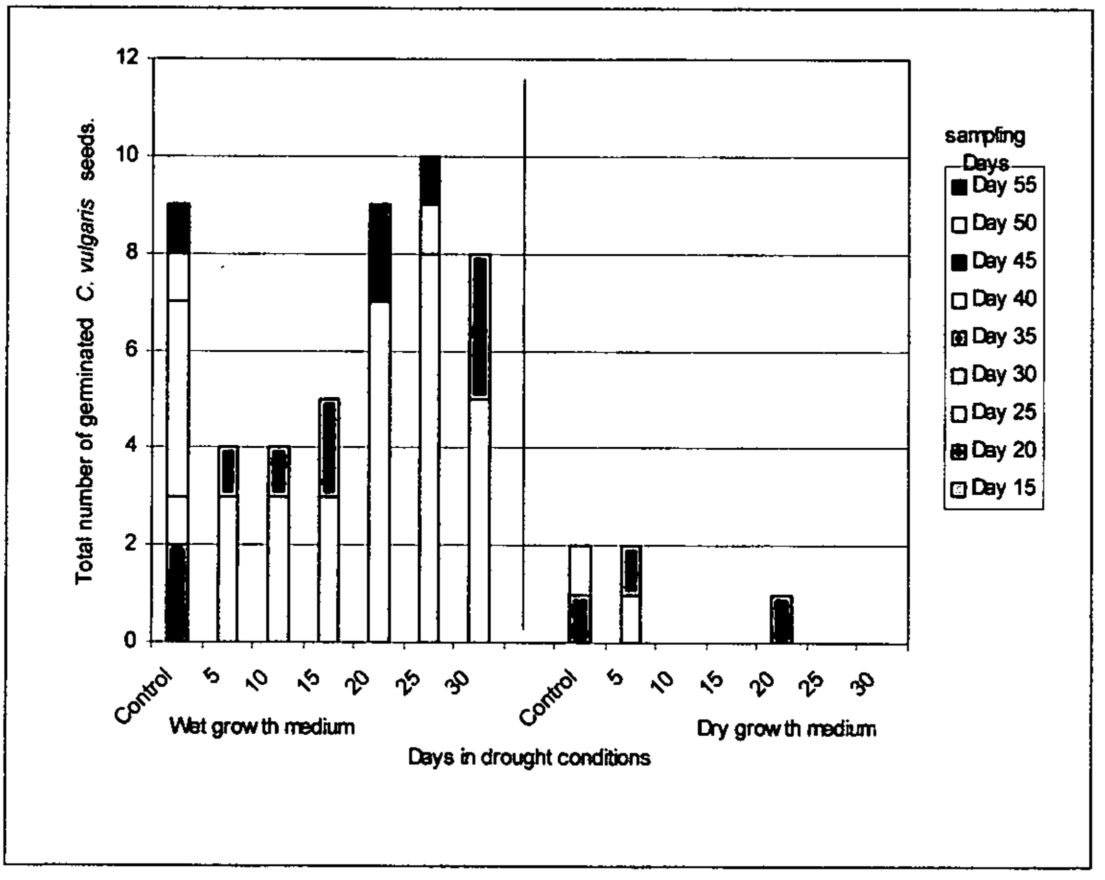


Figure 6.2 Germination of *C. vulgaris* seeds on wet and dry growth media with various times in drought conditions, same time in optimum germination conditions (accumalative total from 15 seeds).

6.5.3 Experiment 2.

In experiments 1 it was noted that the recorded number of *C. vulgaris* seeds germinating on the 'wet and dry' controls was different. As the controls spent only a short time in drought conditions during experimental set-up this study was undertaken to investigate potential germination of *C. vulgaris* seeds within the first five days.

This experiment, although similar to Experiment 1, was conducted in a different order to ensure seeds in the 'controls' were quickly moved from dry to controlled conditions, and did not remain in 'dry' conditions whilst the whole of the experiment was set up. However, this removed randomness from the experiment as a new set of samples was prepared for each treatment.

Two disks of filter paper (Whatman No. 1) were placed in each 9cm diameter Petri dishes and were either watered with 15ml of water (n=3) or left dry (n=3). Five *C. vulgaris* seeds were placed on the filter paper and Petri dishes placed in drought conditions (temperature and light as experiment 1). A new set of Petri dishes were prepared every 24 hours and added to the drought conditions for 120, 96, 72, 48, 24 and 0 hrs (control), before being watered (15ml) and receiving controlled conditions (as experiment 1). Petri dishes were watered (5ml distilled water) every 12 hrs. Seedlings were counted and removed on radicle emergence, any 'mouldy' seeds were removed and all data were recorded. All Petri dishes spent the same time in controlled conditions (n=19 days).

6.5.3.1 Statistical analysis.

Data were first tested for homogeneity of variance. A one-way ANOVA was performed using SPSS statistical package (version 10.0) to test differences in germination rate of C. *vulgaris* seeds on wet or dry peat under various drought treatments.

6.5.4 Results of experiment 2.

Results from a one-way ANOVA showed there was a significant difference between numbers of germinated seeds sown on wet or dry growth medium $F=5.042$, ($P<0.05$).

The total number of *C. vulgaris* seeds that germinated were 76 and 57 for 'wet' and 'dry' treatments respectively. Thirteen *C. vulgaris* seeds germinated on the wet peat control and 14 on the dry control. (Figure 6.3).

The lowest number of germinated seeds recorded (6) was on the 'dry' treatment, which had been in drought conditions for 4 days.

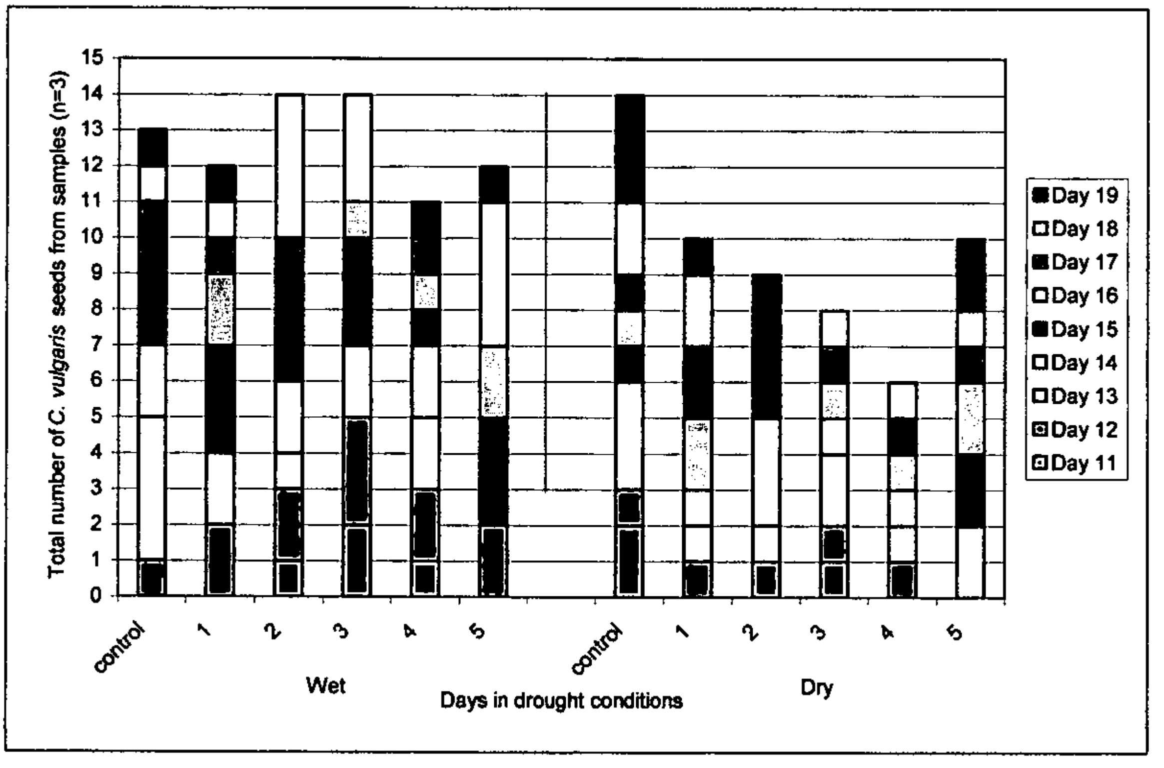


Figure 6.3 Germination of *C. vulgaris* seeds on wet or dry filter paper in controlled conditions following periods in drought conditions. (Cumulative total from 15 seeds).

6.5.4.1 'Mouldy' and un-germinated seeds.

The number of 'mouldy' (unidentified fungus) seeds was higher in the 'dry' compared with 'wet' condition (12 and 8 respectively). Seeds that did not germinate or became mouldy were "wet' treatment 6 (7%) and 'dry' treatment 21 (23%).

6.6 USING POLYACRYLAMIDE GEL TO IMPROVE GERMINATION AND GROWTH CONDITIONS FOR POST-WILDFIRE MANAGEMENT.

To measure the potential of polyacrylamide gel to increase the germination and growth of two grass species used in moorland restoration post-wildfire two studies were undertaken, one in a growth cabinet (section 6.6.1) and on the Stalybridge research site (section 6.6.3). The grasses (*Agrostis castellana* (Highland Bent) and *Festuca rubra* sub-*spp commutata* (Chewings Fescue)) were used within these experiments due to short germination time (2 days): grass species chosen were also selected from the species used on Darwen Moor in the post-wildfire management of 1995 (see section 2.3).

6.6.1 Experiment 3.

To test if polyacrylamide gel had an inhibition effect, hindered or enhanced germination of grass species (see section 6.2.2) an investigation was conducted in a growth cabinet. Sand was used in this experiment as it is inert and drains freely, with results showing the effect of polyacrylamide gel on germination. Set up of experiment was similar to that used by Woodhouse and Johnson (1991) to test inhibition of lettuce seed germination by gels.

Dry cross-linked polyacrylamide gel (Phostrogen Swellgel) was mixed with air-dried washed horticultural sharp sand (max. depth 5mm) to give a series of treatments. Three application rates of gel were used: 1g/1000cm^3, 2g /1000cm^3 and no gel (control). Sand (90g) and gel treatment were mixed well and placed in shallow plastic trays (9cm diameter). Three watering regimes with distilled water were used: i) 30ml added at start of experiment ii) water added until sand was saturated and gel fully hydrated and iii) 50ml with additional 5ml added every 48hrs; these represented respectively, limited water, free water followed by drought and free water always available. Trays were left to stand for 48hr to allow polyacrylamide gel to expand to full capacity.

A set of trays (3 gel treatment x 3 watering regimes) with three replicates (n=27) was prepared for each of the two species *A. castellana* and *F. rubra.* Each tray was sown with twenty seeds of either *A. castellana* or *F. rubra.*

The number of germinated seeds in each tray was recorded after 30 days. A contingency table was prepared to test association between watering regimes and gel treatment on the germination of *A. castellana* and *F. rubra.*

6.6.2 Results of experiment 3.

Although germination and growth of both *A. castellana* and *F. rubra* seedlings generally followed the same pattern (Figure 6.4 and 6.5), there was no significant association between gel applications and watering regime for *A. castellana* (Figure 6.4).

However, there was a statistically significant association between gel application and watering regime in the germination and growth of *F. rubra,* $\chi^2/_4$ 12.63167, ($P<0.05$). Where water was limited (30ml at start) there was less germination in the 2g gel treatment when compared to the 1g gel treatment (0.3 to 3 respectively) and both of these were lower than the control. Where free water was given at start of experiment and where seedlings were watered every 48hr both the 1g gel and the 2g gel treatment showed an increase in seedling germination when compared to the control.

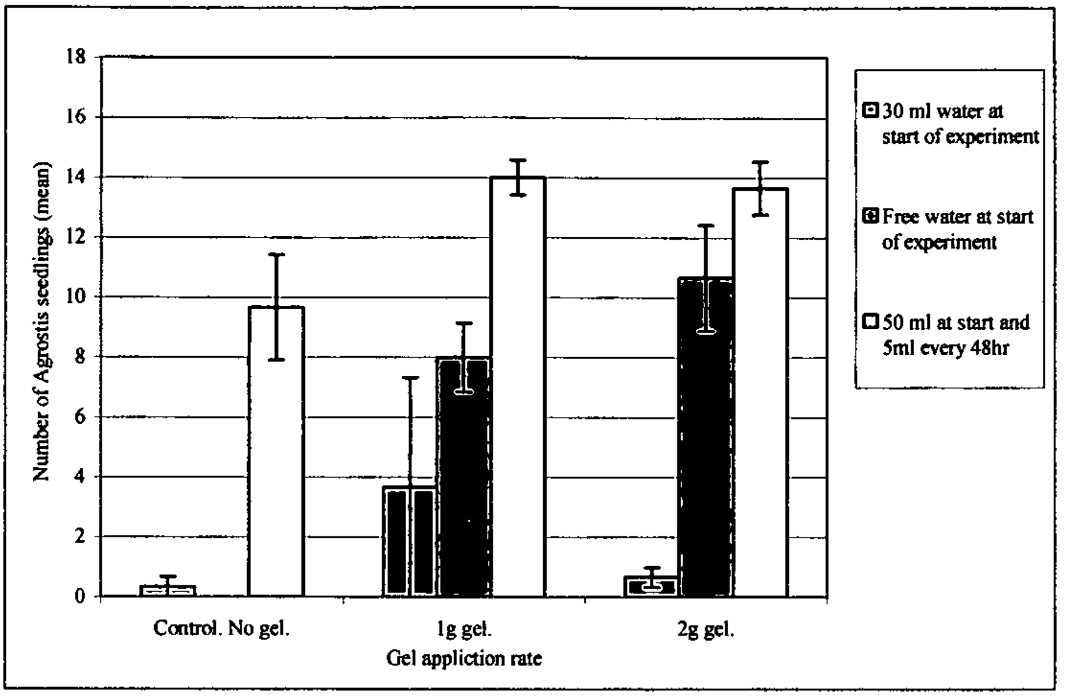


Figure 6.4 *A. castellana* seedlings counted at 30 days after sowing on air-dried horticultural sand with various gel treatments and watering regimes. (Data mean ± SE, n=3).

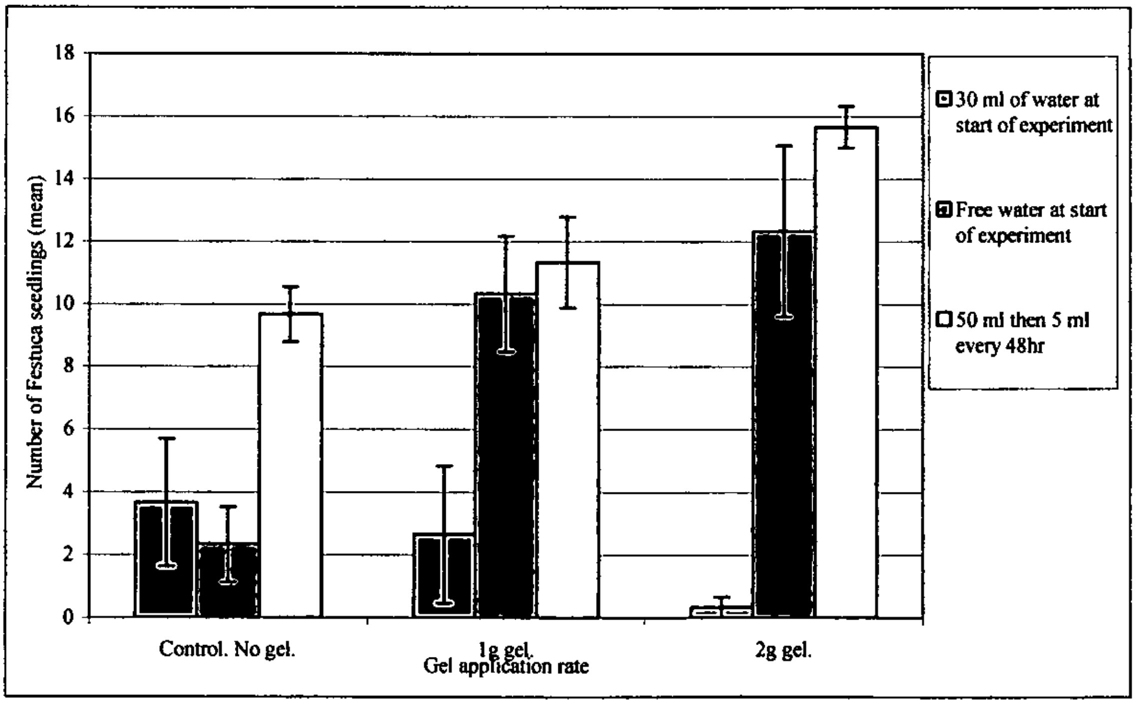


Figure 6.5 *F. rubra* seedlings counted at 30 days after sowing on air-dried horticultural sand with various gel treatments and watering regime. (Data mean ±SE).

6.6.3 Experiment 4.

To investigate the potential of a polyacrylamide gel to increase germination and growth of grass species an experiment was set-up at the Stalybridge research site in an area of deep bare peat.

As discussed in Chapter 3 the counting of pixels to calculation vegetation cover within a digital image is possible using Adobe photoshop. Schooler and McEvoy (2006) used this method to measure damage by beetles on *Lythrum salicaria* leaves; images of leaf damage were assessed using Photoshop to differentiate the black 'damaged' areas from light-green 'undamaged' areas on each leaf. Riegl *et al.* (2005) also used pixel count to calculate biomass of drift macroalgae. This method of estimating vegetation cover was used within this experiment.

Treatment sites, each 0.5 x 0.5m, were dug down to 0.1m and the top peat broken up by hand to a fine tilth. All sites (n=6) were treated with NPK Osmocote slow release 15-9-9 fertiliser (150kg/ha) and lime (1000kg/ha) (Kays Horticultural Products), an application rate similar to Anderson and Radford (1988). Three of the sites were also given an application of gel, from the results of experiment 3 it was decided to use $1g/1000cm^3$. All were evenly applied and dug into the top 0.1m of peat. All sites were seeded with a mixture (50/50 by weight) of *A. castellana* and *F. rubra* seeds (application rate 90kg/ha). Sites were covered with chicken wire (50mm mesh), held down by pegs and large stones; to protect the emerging grass shoots from sheep.

The first attempt to set up this experiment (29th June 2004) was destroyed by a single storm, which filled up the space beneath the chicken wire with blown and washed-in peat.

The experiment was set up again on 12th July 2004 and subsequently surveyed five times (12th Aug. 2004, 2nd and 28th Sept. 2004, 18th March 2005, 22nd Sept. 2005). Sampling was carried out by digital photography of the $0.25m^2$ plots; images were transformed keeping the perspective correct as in section 3.3.1.1. Percentage plant cover was calculated by pixel count. Using the 'Wand' tool within the Adobe Photoshop, all green pixels (vegetation) were selected, (image size was increased in size to enable pixel selection when appropriate). In Adobe Photoshop select Image, choose

Histogram dialog box, which gives the statistics of the image i.e. the number of pixels in the whole image and the count of pixels in the selected pixels. Percentage of pixels representing grass was then calculated.

6.6.3.1 Statistical analysis.

Data were arcsine transformed due to the recorded vegetation cover of 100% (Zar 1995). An ANOVA with repeated measures using the SPSS statistical package (Version 10.0) was used to test differences in vegetation cover between those samples with or without polyacrylamide gel. The assumption of sphericity in repeated measures ANOVA was overcome by using the Greenhouse-Geisser adjusted P value (Kerr *et al.* 2002).

6.6.4 Results of experiment 4.

The results from the ANOVA showed there was no significant difference between grass species grown on the Stalybridge research site with or without a gel application ($p>0.05$), results presented in Figure 6.6.

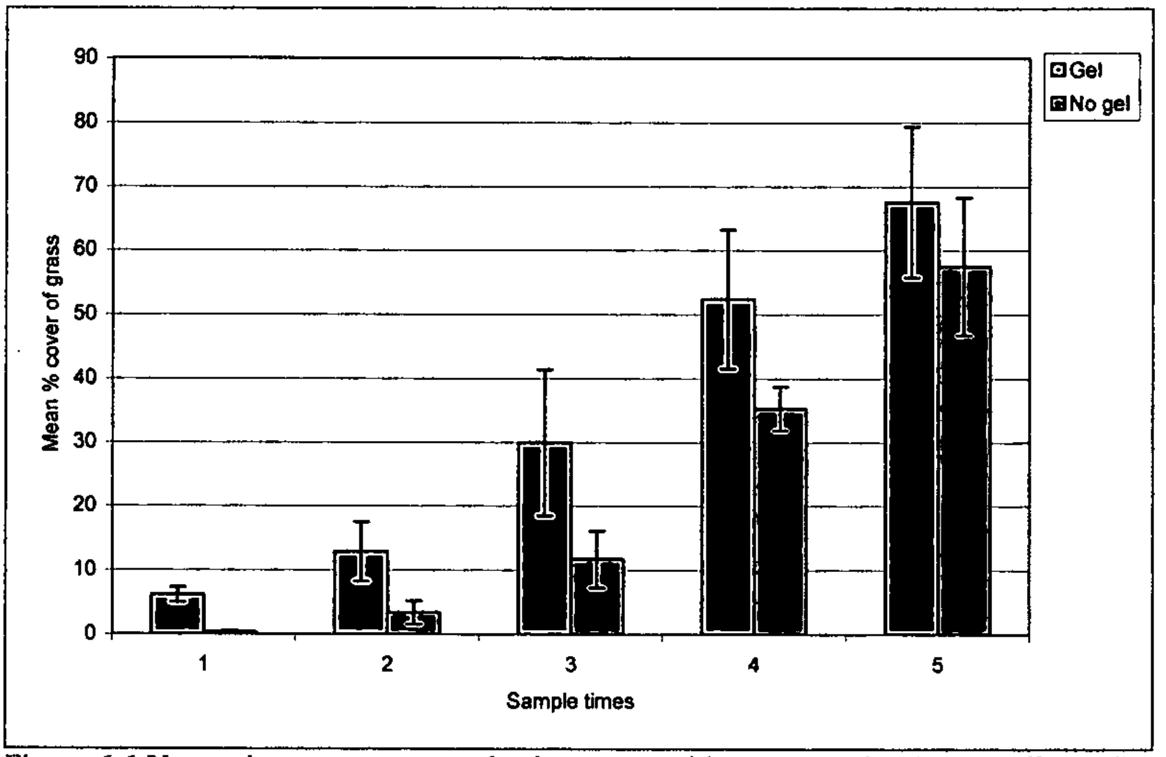


Figure 6.6 Vegetation cover on sample sites sown with grass species (*A. castellana, F. rubra*) an application of fertiliser, lime and with or without polyacrylamide gel. (Data mean ± SE, n=3).

Figure 6.7 and 6.8 show examples of digital images of vegetation cover from which percentage cover was calculated, full set of data is provided in Appendix 7.

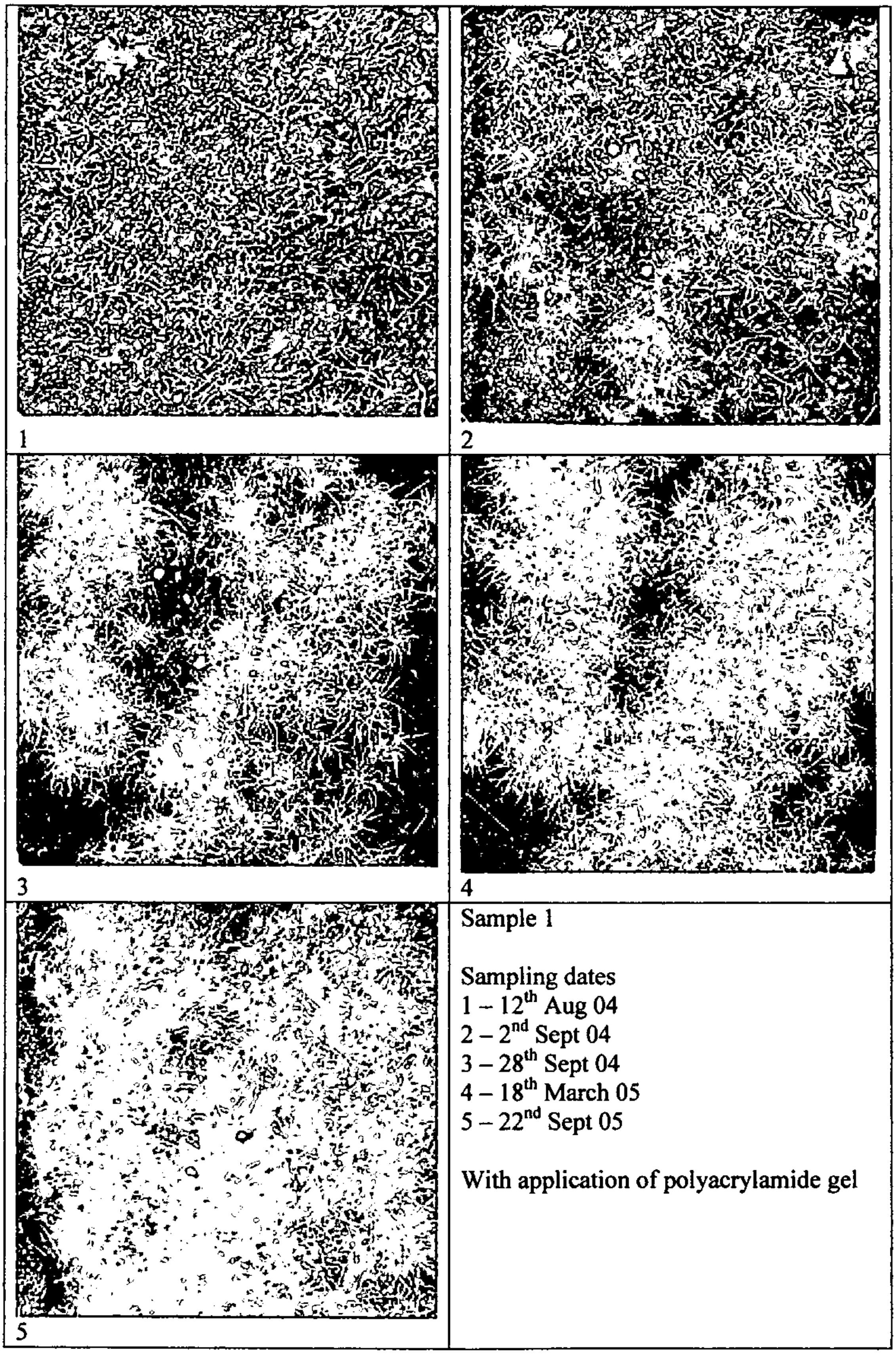


Figure 6.7 Digital images of vegetation cover of one plot with an application of polyacrylamide gel, lime, fertiliser and sown with mixed grass species (*A. castellana, F. rubra*) over five sample times.

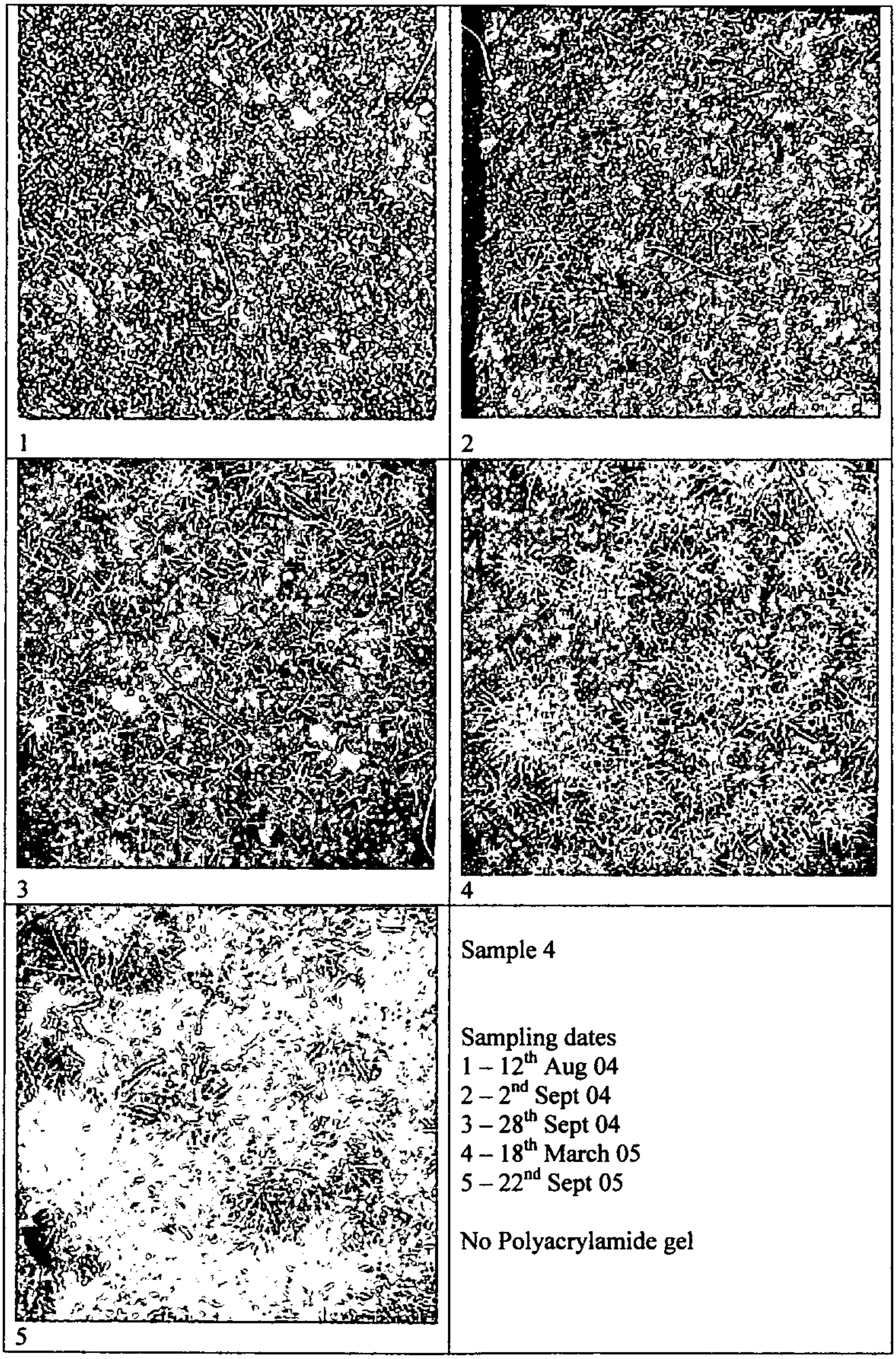


Figure 6.8 Digital images of vegetation cover of one plot with an application of lime, fertiliser and sown with mixed grass species (*A. castellana, F. rubra*) over five sample times. Polyacrylamide gel was not applied to this plot.

6.7 CHAPTER DISCUSSION.

6.7.1 Collected environmental conditions data.

Data of environmental conditions collected for seventeen months showed the range of temperature and water content of the bare peat on exposed upland moorland post-wildfire. Datalogger results showed there was limited opportunity for germination of *C. vulgaris* seeds when results were compared to optimum conditions as suggested in literature (Gimingham 1972, Grime *et al.* 1996). The combination of appropriate temperature (10 – 28°C) and water content of the peat (field capacity) was only reached in three months (June, July and August 2004), with 23, 19 and 15 consecutive days being recorded respectively; with August 2004 just being the minimum period of optimum conditions of 15 days (Grime *et al.* 1996). As expected, there were higher fluctuations in diurnal temperature recorded in the summer than the winter months (Figure 6.0 and Appendix 6). These fluctuations in temperature have been reported to enhance germination of *C. vulgaris* (Gimingham 1972). High temperatures were recorded, over 28°C, which is the highest optimum germination temperature of *C. vulgaris* (for example, August 2004), this can also increase evaporation (Bannister 1976) and shows that extreme conditions as suggest by (Bannister 1976) are a regular feature of a bare degraded moorland post wildfire.

There were also large fluctuations in the water content of the peat, particularly in the winter months (Figure 6.1 and Appendix 6), suggesting high precipitation but a relatively rapid loss of water from drainage of the peat or overland flow as the peat was already at field capacity. These actions of water may lead to erosion of the peat and further degradation of the site and removal of any seed deposited.

If natural regeneration of *C. vulgaris* is to occur on bare moorland then the seeds have to survive these poor and highly fluctuating environmental conditions. Survival of seeds and seedling may be very poor if optimum conditions are not maintain for at least the germination period (0-14 days), although the process of imbibition has been shown to be reversible during early stages in some seeds (Opik and Simon 1963). It is accepted that this study did not measure the climate of microsites, and that germination and establishment of *C. vulgaris* seedlings may be occurring in these sites, although the results from the survey on Stalybridge site (Appendix 1) show regeneration of this site is very slow. Regeneration of vegetation post-wildfire on this site may be limited by the availability of microsites or by the availability of seed (Eriksson and Ehrlen 1992). The dispersal rate of *C. vulgaris* seeds into a moorland site post-wildfire is investigated in Chapter 7.

If, as predicted by UKCIP 1998 scenario (Hulme and Jenkins 1998) the precipitation in the north-west of England is to increase by 2080, but with a decrease in the summer months then regeneration management on the research sites and any upland moorland sites will become more problematic. This may lead to an increase in wildfires in the dry summers and consequently more erosion on un-vegetated sites. There are many other impacts from global warming that may affect upland moorland. For example, elevated CO_2 which may affect mycorrhizal fungi colonization (Olsrud *et al.* 2004). Increased damage to *C. vulgaris* plants also occurs when drought coincides with increased nitrogen supply (Gordon *et al.* 1999). On a wider scale, global warming will cause extensive biological changes and the scientific literature suggests largre changes to ecosystems, habitats and biodiversity, for example see De Valpine and Harte, (2001) Parmesan and Yohe (2003), Thomas *et al.* (2004), Malcolm *et al.* (2005), De Boeck *et al.* (2007).

6.7.2 Experiments 1and 2.

Results from this set of experiments (1 and 2) showed a significant difference ($p<0.05$) in *C. vulgaris* seed germination rates within the treatments studied. A higher germination rate was recorded in all experiments for seeds sown on wet peat, irrespective of time in dry conditions when compared to seeds sown on wet growth medium.

The controls in experiment 1 also showed a reduction in germination on the dry peat despite only experiencing a few hours on the dry peat during experimental set up. Experiment 2, which was conducted so this time was reduced to only minutes showed there was no difference between wet and dry 'controls'. However, there was a reduction of germinated seeds on dry growth medium compared to wet conditions over the period of investigation (5 days) and this difference was significant ($P<0.05$). There was also an increased incidence of mouldy seeds under dry condition (12 seeds on dry to 8 seeds on wet medium) and seeds that remain un-germinated at the end of the experiment (21 to 6). Numbers of dead seeds as opposed to seeds that had entered dormancy was not investigated in this study. Seeds could have been examined, and recorded dead if their contents were soft and brown as opposed to a firm white embryo and endosperm of viable seeds (Pons 1991). This failure to examine seed viability was a drawback of this experiment and further work may be needed to establish mortality rate of *C. vulgaris* seeds in drought conditions. However, the results do show that seeds falling on dry peat will become dormant or die in a very short period of time and will not readily germinate even if environmental conditions become conducive to germination of *C. vulgaris* at some later time. This is in contrast to *C. vulgaris* seed that on dispersal fall into the litter under the parental plant and enter the seedbank; these seeds have been shown to survive for many years (Miller and Cummins 1987). Therefore, longevity of *C. vulgaris* seeds in drying environmental conditions does not necessarily correlate with their persistent in seedbanks, which supported the results of Thompson (2000). This suggests that regeneration of moorland sites, post-wildfire, from natural establishment of *C. vulgaris* seed may not readily take place without management to enhance environmental conditions.

As *C. vulgaris* seeds will germinate quickly after seed shedding (see chapter 5) it is suggested that they are non-dormant and therefore may be susceptible to desiccation. This was reported by Tweddle *et al.*, (2003) who showed desiccation sensitivity of seeds was more frequent in seeds that are non-dormant (c.31%) on shedding than dormant (c.9%). This would also explain why *C. vulgaris* seeds do not readily germinate after being in drought conditions and then receive optimum conditions. The implication of this, in terms of moorland management, is that *C. vulgaris* seeds should not be spread onto a dry moor or where conditions are likely to deteriorate without any protection. This was undertaken on Darwen Moor post-wildfire when bales of *C. vulgaris* shoots were spread by volunteers on to the dry black ash, with the *C. vulgaris* shoots spread too thinly to give protection. Although, the moor has been subsequently revegetated with the aid of nurse species (Chapter 4), it must be assumed this post-wildfire management of spreading *C. vulgaris* shoots did not aid regeneration of the moor. However, where the application rate of *C. vulgaris* shoots is adequate excellent re-establishment of *C. vulgaris* is observed (Putwain and Rae 1988, Pywell *et al.* 1996).

If, as suggested by these results the *C. vulgaris* seeds are dormant, their dormancy resembles combinational dormancy under Baskin and Baskin's (2004) classification of dormancy; a combination of physiologically dormancy and physical dormancy. In physiological dormancy seeds often need periods of light, cold or warmth to break dormancy, *C. vulgaris* seeds do need light (Grime 1979) and Gimingham (1972) suggests germination is enhanced by fluctuating high temperatures, although cold stratification does not enhance germination (Mallik and Gimingham 1985). With physical dormancy the seed coat is resistant to water uptake and seeds will remain dormant until some factor renders the seed coat permeable to water. This factor includes high temperatures, widely fluctuating temperatures, fire, drying, and freezing/thawing. As *C. vulgaris* seeds can survive many years in a seedbank and under parental plants in wet or damp conditions, it is suggested they have an impermeable seed-coat. Seeds with an impermeable seed-coat may possess a strong physical germination barrier (Baskin and Baskin 1998). Also the dormancy of *C. vulgaris* seeds does not resemble the morphological or morphophysiological classification of dormancy (Baskin and Baskin 2004), where seeds are not mature on dispersal, as *C. vulgaris* seeds are fully developed and can germinate at time of dispersal as demonstrated in Chapter 5.

6.7.3 Experiments 3 and 4.

It was suggested by Woodhouse and Johnson (1991) that gels may have an inhibitory effect, at high concentrations, on germination of some species of seeds. However, experiment 3 showed that polyacrylamide gel had not hindered germination of *A. castellana* and *F. rubra* seeds where water was either freely available at the beginning or throughout. However, with an increased application of gel (2g/1000cm^3) there was a decrease in germination of *F. rubra* seeds. This may also support the findings of Green *et al.* (2004) who suggested that water absorbed by polyacrylamide gel is held in the gel and may not be available for plant uptake. These results determined the use of an application rate of 1g per 1000cm^3 for the study of improving germination and growth conditions at Stalybridge.

Although the results of the trials on the Stalybridge site showed more grass cover in treatments with an application of polyacrylamide gel when compared to treatments without the gel, this difference was not significant. This is in contrast to Huttermann *et* *al.* (1999) who showed the addition of hydrogels to soil prolonged the survival of *Pinus halepensis* seedlings subjected to drought. The environmental conditions may have been too extreme for the application of gel to be of aid for plant growth, for example both peat and gel dried. The water within the gel may have been held and not available for plant uptake, although results from experiment 3 do not support this conclusion.

As the grass cover was not significantly different between the control and the gel treatment in the trials on the Stalybridge site it must be assumed that the application of polyacrylamide gel did not influence establishment of grass. Therefore, the method of experiment set-up may have enhanced vegetation regeneration. Breaking up the top 0.1m of peat, protecting with chicken-wire and provision of large stones around the sample plots (used to hold wire in place) may have provided 'safe' sites for seeds, protection from wind or creation of a local micro-climate. However, the complete loss of the first set-up of this study showed how vulnerable these sites are post-wildfire if post-wildfire management is unfortunately undertaken before unsuitable weather occurs, then extensive labour and expensive fertiliser and seed can be wasted.

Calculating the vegetation cover by counting pixels in the images of sample sites re-vegetated with grass species was possible as only one type of vegetation (grass) was present on a uniform coloured background (peat). This method proved straightforward to administer and gave a quantitative result, which was non destructive and did not require a large sampling time spent in the field.

In conclusion, the results from the datalogger showed the extreme environmental conditions that may be experienced on an upland moor when all the vegetation has been removed by wildfire. When compared to optimum requirements, as given in literature, the results show there may be limited opportunity for germination and establishment of *C. vulgaris*. However, seeds may be protected from these extreme environment conditions in a 'safe-site' with a microclimate that promotes seedling establishment. Poor regeneration of the Stalybridge site may be limited by availability of these 'safe-sites'. Germination of *C. vulgaris* seeds were shown to be inhibited by drought conditions and did not readily germinate even when optimum conditions were provided. Polyacrylamide gel did not enhance the establishment of grass species in a moorland environment.

7.0 Chapter 7

DISPERSAL AND REGENERATION POTENTIAL OF *CALLUNA VULGARIS* SEEDS ON TO BARE PEAT POST-WILDFIRE.

7.1 *INTRODUCTION.*

Moorland sites post-wildfire often receive little or no management and are left to natural recolonisation from the surrounding vegetation, which will depend on dispersal ability of these plants to colonise the damaged site. This chapter investigates the dispersal potential of *C. vulgaris* seeds, in terms of range and quantity, and their ability to colonise burnt moorland.

7.2 *BACKGROUND TO THIS STUDY.*

7.2.1 Seed dispersal.

Seed dispersal may influence the population biology of higher plants by contributing to changes in population size (Harper 1977) and to the formation of new populations by colonisation (Willson and Traveset 2000). Plants use a variety of methods for seed dispersal, for example, dependence on frugivorous animals spreading the seeds after eating the fleshy fruits (Jordano and Schupp 2000) and numerous aerial modes of wind-dispersal seeds (Minami and Azuma 2003). The spatial distribution of dispersed seeds around their source has been termed a 'seed shadow' (Janzen 1971). This may relate to dispersal from a single parent or multiple parents. Two factors can be used to describe seed shadows, (i) the relationship of seed numbers or density to the distance from source and (ii) the directionality with respect to the source (Willson and Traveset 2000).

Due to the size of *C. vulgaris* seeds, mean mass of 0.03mg, with dimensions of 0.7 x 0.5mm (Grime *et al.* 1996) it has been suggested that they are wind dispersed and may travel up to 0.25km in winds of 30-40m sec^{-1} (Nordhagen 1937). *C. vulgaris* seeds have been collected at a distance of 80m from a transplanted source plant within grassland, although 91% of such seeds fell within 0.8m of the parent plant (Bullock and Clark 2000). Surrounding vegetation may interfere with the dispersal of seeds (Nathan and

Muller-Lanau 2000, Bullock and Moy 2004) causing seeds to be deposited close to the plants with a 7-15 fold increase compared with background numbers (Bullock and Moy 2004). In stands of *C. vulgaris* in the north-east of Scotland the total number of seeds (m^{-2}) deposited in the four growth phases were: - pioneer: 18,910; building: 169,010; mature: 198,580; degenerate: 33,900 (Barclay-Estrup and Gimingham 1994). Bullock and Clark (2000) also recorded a density of 157,504 m^{-2} of collected *C. vulgaris* seeds at 0.8m from seed source.

The number of *C. vulgaris* seed capsules and the seeds within are affected by size and age of plant, growth phase, habitat, site altitude and a host of environmental factors and will fluctuate annually dependant on climatic conditions. Seed shedding from *C. vulgaris* occurs from September onwards and seeds may overwinter on the plant (Grime *et al.* 1996). Due to presence of a persistent calyx, capsules can only split along the upper side, which restricts seed shedding to windy periods (Gimingham 1972). The number of seeds in each range capsule range from 0-41 (overall mean 10 seeds) (Legg *et al.* 1992), 2-37 (Traynor 1995) and a mean yield of 14-19 seeds at 300m a.s.l. (Miller and Cummins 2001). All of these results came from studies on capsules harvested from the *C. vulgaris* plants. Capsules that have become naturally detached from the plants may contain fewer seeds, Legg *et al.* (1992) suggests (from unpublished data) that each capsule may only contain 2.2 to 3.7 seeds with half of the capsules examined containing no seeds. Also, if it is assumed that several seeds dispersed in a single capsule are unlikely to produce more than one effective colonising unit, then the colonising potential is only half the capsule-rain density (Legg *et al.* 1992). Traynor (1995) has also shown percentage of viable seeds within the capsules can range from 66% to 90% depending on site and year.

7.2.2 Removal of deposited *C. vulgaris* seeds.

Seeds that fall on bare peat are vulnerable to harsh conditions and may not germinate or increase the seedbank (see Chapter 1). Cerda and Garcis-Fayos (2002) suggest that size and shape of seeds influence removal rate from the soil surface after seed dispersal by water erosion. As seed size increases, the removal rate decreases; seeds with a mass between 10 and 50mg have the lowest removal rates. Small seeds, such as *C. vulgaris* (mass 0.03mg), flow easily and, if spherical in shape, favour rolling down slope

(Fagundez and Izco 2004). Wind dispersed seed capsules may also be important for long distance dispersal (Legg *et al.* 1992).

7.2.3 *C. vulgaris* seeds used in moorland management.

Direct sowing a *C. vulgaris* seeds on to moorland sites has been used in many restoration projects. Anderson (2004) suggests an application rate of 17kg ha^{-1} of uncleaned *C. vulgaris* capsules is sufficient for reseeding in restoration of *C. vulgaris* on *Molinia* grassland. With clean seed (capsules removed) an application rate of 600gms ha^{-1} is recommended (Anderson 2004) as there are approximately 12,000 seeds g^{-1}, this gives a mean coverage of 720 seeds m^{-2}. Harvested *C. vulgaris* shoots are also used as a supply of seed, this method can produce 1538 seeds kg^{-1} of shoots or 3059 m^{-2} of heath (Pywell *et al.* 1996). This method may also provide protection to the seeds and seedlings from the spread litter.

Many different quantities of seeds, capsules or cut shoots of *C. vulgaris* have been tried in moorland restorations projects and trials with varying results (Putwain and Rae 1988, Pywell *et al.*1996). A shoot application rate of 1.8kg m^{-2} has been shown to be adequate for regeneration of *C. vulgaris* on mineral wastes (Pywell *et al.*1996). Trials on Peak District moorland using 312g of shoots m^{-2} gave variable results depending on site and experimental treatment (Tallis and Yalden, 1983).

7.2.4 Seed shadow prediction.

Many studies try to predict the seed-shadow of plants with reference to seed size and wind speeds, for example Sharpe and Fields (1982), Jongejans and Schippers (1999), Bullock and Clark (2000), Pielaat *et al.* (2006). However, within this investigation focus is on the actual number, direction and distance of *C. vulgaris* seeds located from a known source. Number of *C. vulgaris* seeds deposited on the bare peat was expressed as number of seeds per square metre to enable results to be compared to the number of seeds used in moorland management.

7.3 RESEACH AIMS.

The aims of this chapter are to investigate the dispersal ability in terms of distance and quantity of *C. vulgaris* seeds from a known source.

Experiments were conducted over two years, (2003 and 2004) at the Stalybridge research site (section 2.4). The first year concentrated on experimental design and the feasibility of trapping and collecting seed samples from upland moorland. A seed-trapping trial was completed to test the selected experimental design (section 7.4). Collection of quantitative data and dispersal range of *C. vulgaris* seeds was completed in year two from radial seed-traps using translocated plants and from a 'natural island' of *C. vulgaris* plants (section 7.5).

7.4 *EXPERIMENTAL DESIGN AND TRIAL.*

7.4.1 Materials and methods.

7.4.1.1 Seed-trap design.

Due to potentially harsh climatic conditions, including high winds and precipitation, seed-traps were designed to capture seeds but not to become flooded or blown away. A seed trap design similar to that used by Bullock and Clark (2000) was considered, but with an addition anchorage point. Two 9cm diameter plant pots were place one within the other, with the inner pot shortened and its base removed. A 30cm circle of 17g horticultural fleece (N. A. Kays Horticultural Products, Whitehaven) was placed between pots and held in position with an elastic band (8cm diameter). To position the trap in the peat, a hole just large enough to accommodate the trap, was dug with a hand trowel and a metal peg (25cm long with hooked end, similar to a tent peg) was pushed through the lower pot into the peat to hold it in place. Peat was replaced around the trap and tampered down. The top part of the trap remained 1cm above the peat surface so seeds were not blown across the surface and into the trap. A second metal peg was inserted to hold the inner plant pot and trap firmly in place, see figures 7.0 and 7.1.

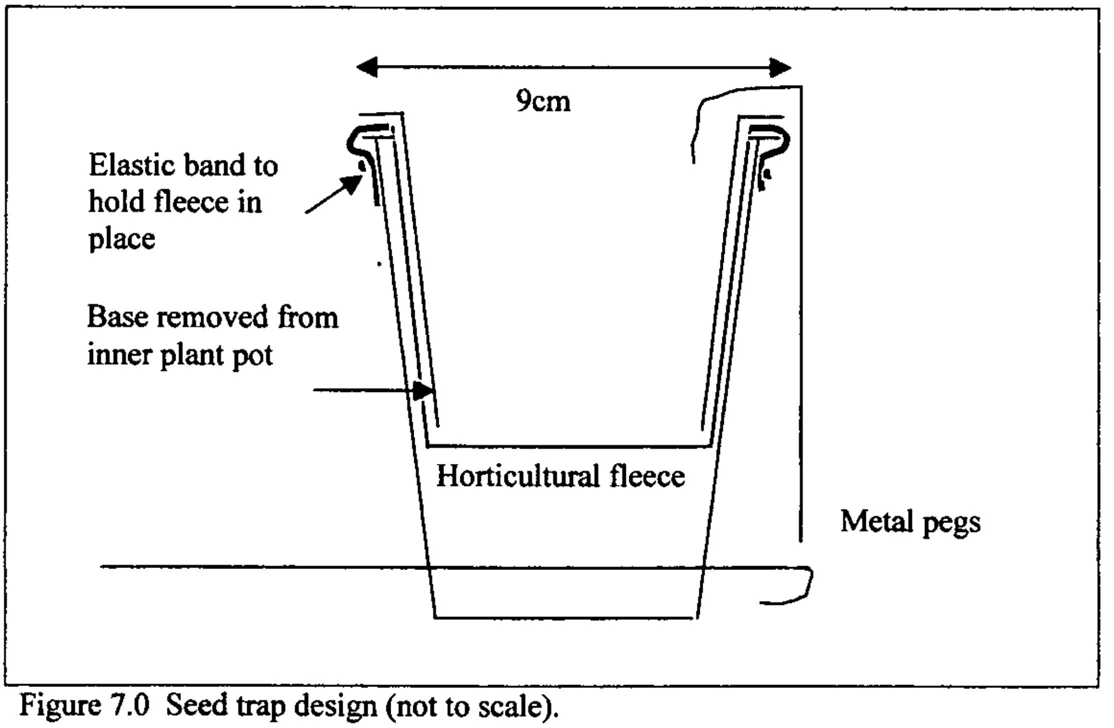


Figure 7.0 Seed trap design (not to scale).

Figure 7.1 An example of a seed trap *'in situ'*, at the Stalybridge research site.

7.4.1.2. Moorland trial to test durability of seed-traps.

To ensure seed-traps would remain in place and capture *C. vulgaris* seeds being dispersed from parent plants, a trial was set up at the Stalybridge research site. Seed-traps were placed along three pairs of parallel transects (1m apart) on bare peat between two large banks of *C. vulgaris* plants. Seed-traps were placed at the edge of the *C. vulgaris* plants (0m) and then at 1, 2, 3, 4, 5, 10m and thereafter every 5m, to 45m, the furthest distance from either bank of plants. An area with a radius of 45m from the centre seed-traps was inspected for the presence of *C. vulgaris* plants; non were found; this ensured seeds falling into the seed traps must have travelled at least the distance from the bank of *C. vulgaris* (45m) (Figure 7.2). The seed-traps were placed on site on 8.9.03.

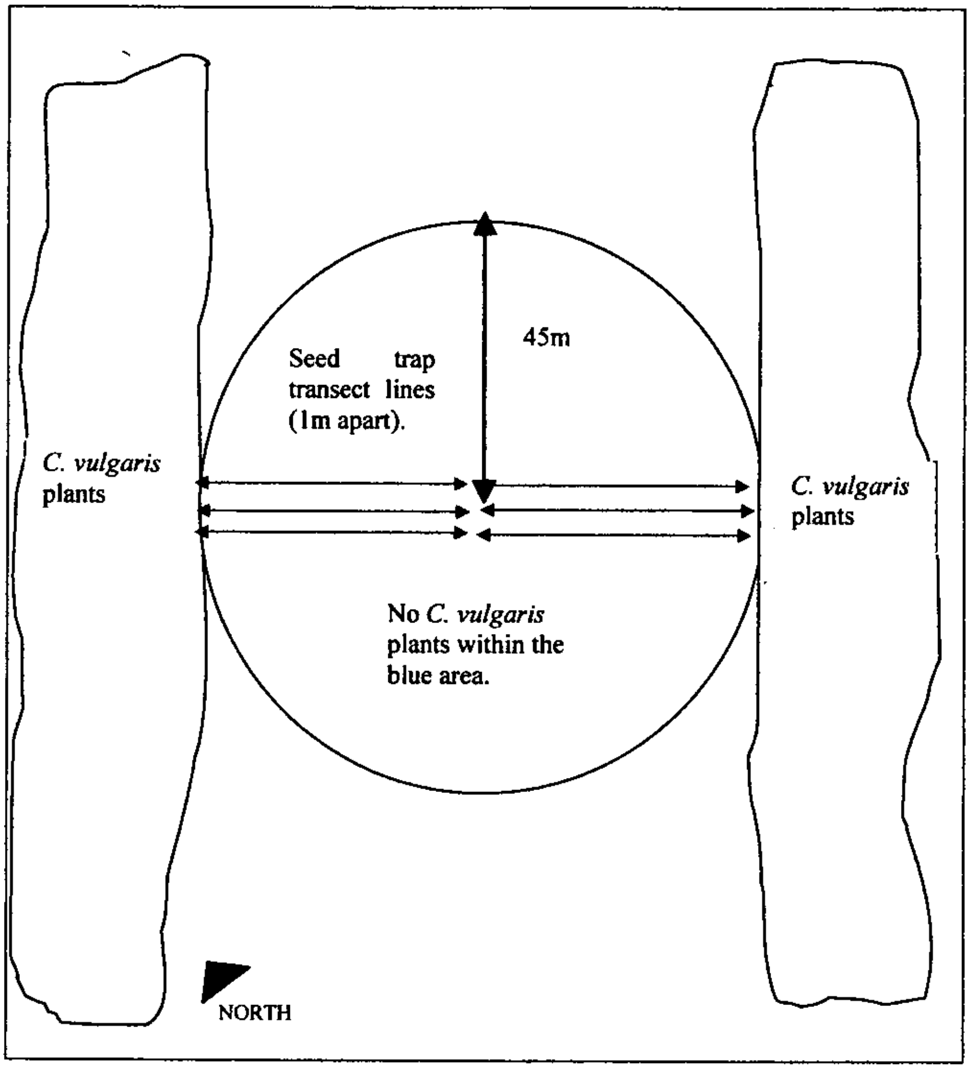


Figure 7.2. Design of linear seed trap experiment. Transects (n=6) were located on bare peat between two banks of *C. vulgaris* plants (not to scale).

At data collection (20.10.03, 19.11.03 and 18.12.03) the fleece and contents, which included blown or washed in peat, were removed and a replacement circle of fleece was inserted into the trap. Fleece samples were placed in individual plastic bags, sealed and labelled appropriately with transect number and distance from seed source. Samples were air-dried and seeds and capsules were identified, counted and recorded. This process was undertaken by sieving (2mm mesh size) a small proportion (approximately 1g) of the air-dried sample on to a white piece of paper with a grid to ensure the entire sub-sample was inspected. The sieved sample was then examined with a hand lens (x 5) and seeds counted and discarded. The process continued until each entire air-dried sample was examined. Although this process was very laborious, *C. vulgaris* seeds were easily identified by their distinct shape (ellipsoid in outline, with a reticulated pattern for testa surface and a yellowish red colour when fresh, Fagundez and Izco (2004)), see figure 7.3. Seeds were also compared to those from a known source. The residue in the sieve was then examined for presence of seed capsules. Data were recorded for each sample.

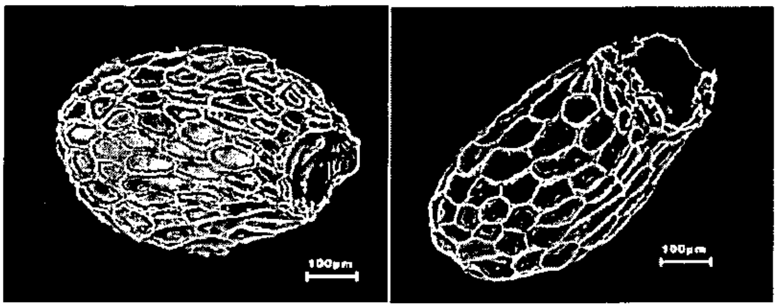


Figure 7.3 *C. vulgaris* seed, showing ellipsoid shape and reticulated pattern for testa, (Adapted from Fagundez and Izco, 2004).

7.4.1.3 Statistical Analysis.

Seed count data were analysed by non-linear regression analysis to determine any relationship between numbers of *C. vulgaris* seeds deposited and the distance from the seed source (Brown 2001).

7.4.2 Results and discussion

Results from the regression analysis showed there was no significant linear and non-linear relationship between number of seeds and the distance they were trapped from seed source. Figure 7.4 shows the number of *C. vulgaris* seeds (m^2) at each sampling point for the six transects.

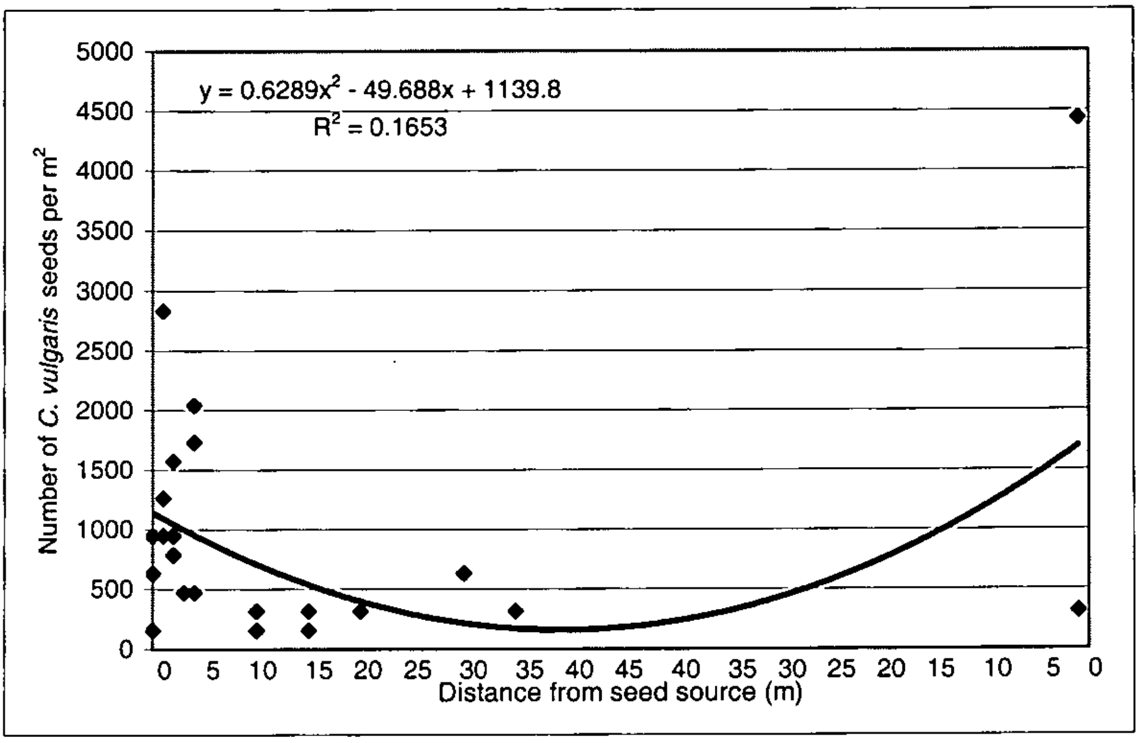


Figure 7.4 Number of *C. vulgaris* seeds (m^{-2}) at each sampling point for the six transects. Best-fit line shows relationship between number of seeds and distance from seed source.

C. vulgaris seeds and capsules were trapped at most collection points up to 35m (52 seeds m^{-2}) and 25m (78 capsules m^{-2}) from source plants, with 56.7% (1,114 m^{-2}) of seeds and 75.5% (969 m^{-2}) of capsules being trapped within 1m of the seed source (Figure 7.5).

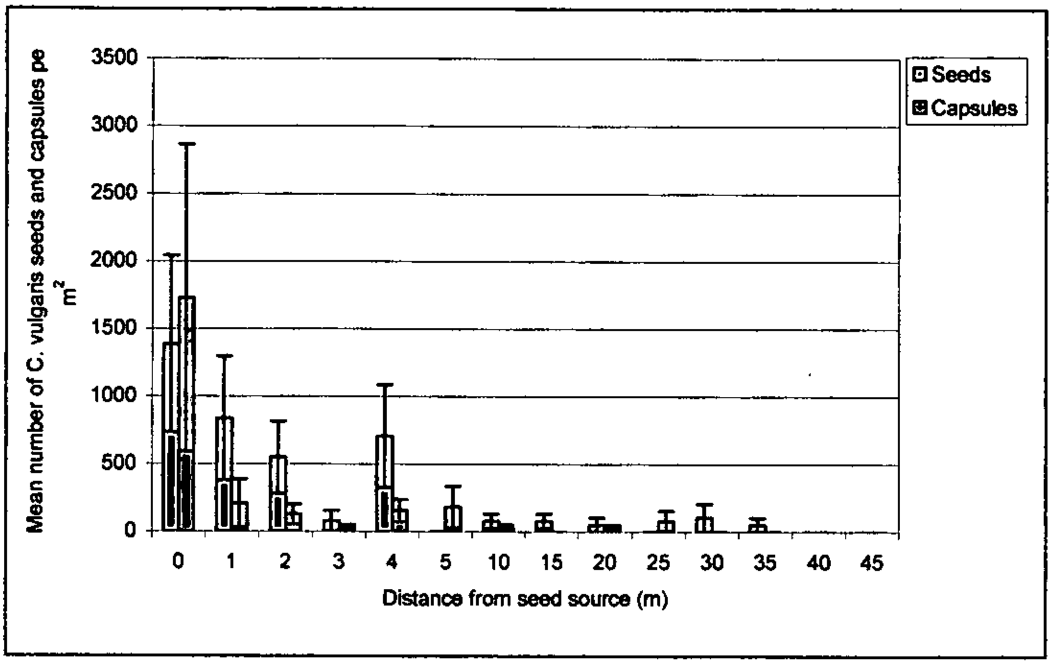


Figure 7.5 Results from the trial seed-trapping experiment, showing distance and quantity of seed and capsules (m^{-2}) trapped (Data mean ± SE, n=6)

This trial experiment was undertaken to test method of trapping, identifying and counting *C. vulgaris* seeds before a large experiment was conducted on the open moorland, all of which was accomplished successfully. The results show more seeds were deposited near the north-west bank of *C. vulgaris* plants than the opposite bank, this may suggest environmental conditions prevailing on the site influenced the seed-shedding. These potential environmental conditions were considered when the next experiment was designed (section 7.5).

7.5 *RADIAL SEED-TRAP EXPERIMENT.*

From the results of the trial seed-trap experiment it was shown the seed-traps would remain in place on open moorland up to 45m from shelter of surrounding vegetation and seed source. Although changing the fleece and collecting samples from the seed-traps was time consuming and difficult work in high winds, it was possible to trap and collect samples from the moor. A seed-trap experiment was designed so any environmental conditions, such as wind direction, would not affect the results. In autumn 2004 a radial seed-trap experiment was set up with transects radiating away from a transplanted central *C. vulgaris* plant.

7.5.1 Materials and methods.

The area chosen for the radial seed-trap experiment was in an unvegetated section of the Stalybridge site within the fenced research area, with a surface of bare peat. It was surveyed prior to the start of the experiment for the presence of *C. vulgaris* plants; none were found within 100m of the proposed transplanted *C. vulgaris* plant site (figure 7.6). This ensured that any trapped *C. vulgaris* seeds and capsules must have travelled at least 50m from a seed source.

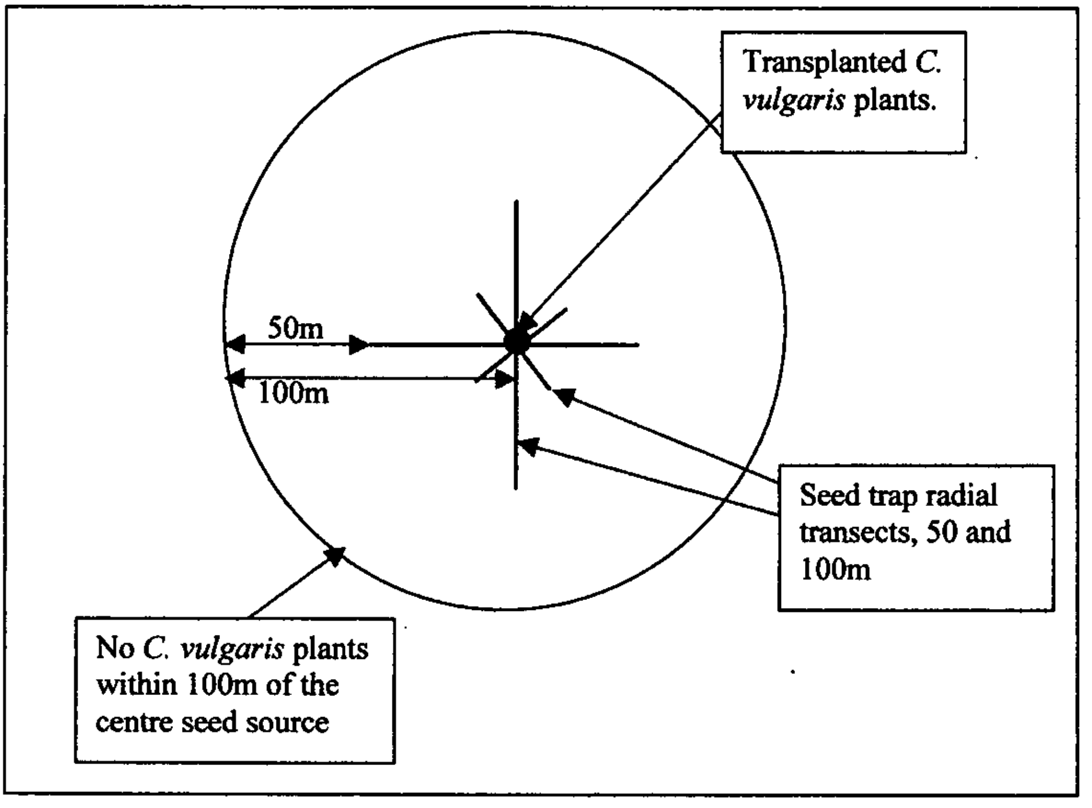


Figure 7.6 Design of radial seed-trap. Central transplanted *C. vulgaris* plants in an unvegetated area (200m diameter) of the Stalybridge research site. Seed-traps were located on the transects radiating out from the centre (not to scale).

In the absence of large *C. vulgaris* plants, due to a fire in the spring of 2003 and good muirburn management (section 2.4), five small *C. vulgaris* plants (total diameter 0.75m x 0.3m high, approx) were translocated from a regenerated area within the fenced research site in early October 2004. Plants had intact roots and were covered in capsules, which were well formed, ripening but not split to release seeds. Timing of translocation was selected to ensure a reliable crop of seeds even if plants were damaged slightly during the translocation process.

Seed traps were located along transects in eight directions from the translocated *C. vulgaris* plants. The first traps were located around the edge of the plants (0m) with the remaining located at 0.5, 1, 2, 3, 4, 5, 10, 20, 30, 40 and 50m along the north (N), South (S), East (E) and West (W) transects. On the north-east (NE), north-west (NW), south-east (SE) and south-west (SW) transects traps were located to 10m. One trap was located at each distance up to 5m, two at 10-30m and four traps at 40 and 50m (n= 112). Where more than one trap was present, they were positioned in an arc at each location with each trap an equal distance from the central *C. vulgaris* plant, and each trap immediately adjacent to its neighbours (Figure 7.7). Method for inserting traps into the peat was as described in Section 7.4.1.1.

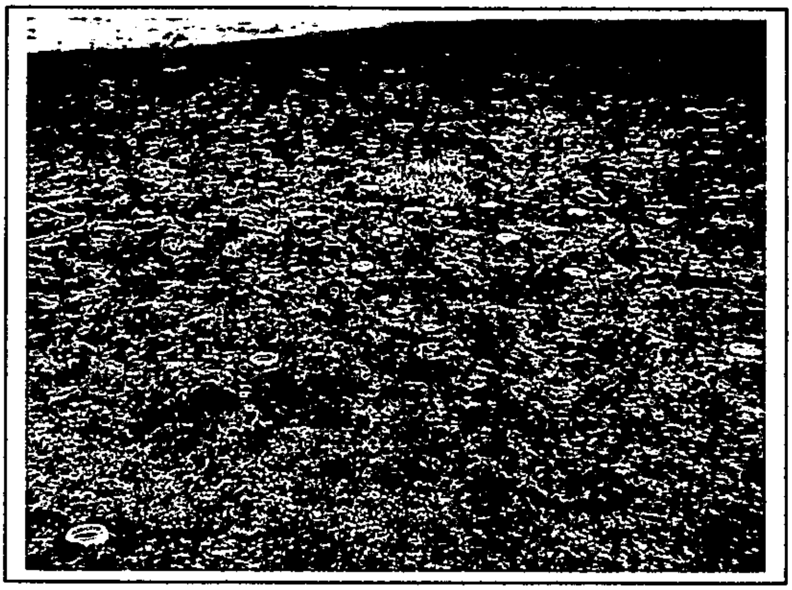


Figure 7.7 Seed-traps in position at the Stalybridge site. Traps located on transects radiating out from centrally translocated *C. vulgaris* plants.

The surface 2cm of the peat plug removed to enable trap insertion into the peat was collected, individually bagged and labelled with distance and direction from potential seed source. Samples were air-dried and examined for the presence of *C. vulgaris* seed capsules. This procedure was used to provide a baseline number of capsules on the peat prior to experimental set up.

Contents of traps were collected twice, at 4 and 14 weeks after experiment set-up (3rd November 2004 and 14th January 2005), within the seed-shedding period. Collected samples were labelled. Contents of the traps were air-dried and numbers of seeds and capsules recorded as described in section 7.4.1.2.

To measure the removal rate of deposited *C. vulgaris* capsules on bare peat, or the difference between those capsules caught in the traps and those deposited directly on the peat; peat samples were collected adjacent to each seed trap position at each sampling time. A metal cylinder (9cm diameter) was pushed into the peat and a shallow (2cm) core removed. These cores were air-dried, sieved (2mm mesh size) to remove peat and the number of *C. vulgaris* capsules counted and recorded.

7.5.2 Seed dispersal from a natural ' island' of *C. vulgaris*.

A similar seed trap experiment was set up using a large island of mature *C. vulgaris* plants (approximately 5m diameter) as the seed source. This island of plants was within degraded bare peat but outside the designated research area. Due to the number of sheep present and the area being accessible to the general public, it was decided to collect peat samples instead of using seed traps. There were no *C. vulgaris* plants within 20m of the island of plants.

Samples cores were taken (9cm diameter x 2cm deep,) along four transects N, S, E and W at 0, 0.5, 1, 2, 3, 4, 5 and 10m. Only *C. vulgaris* seed capsules were identified, counted and numbers recorded (see section 7.4.1.2). Sample collection was carried out on the same days as the radial seed-trap experiment (3rd November 04; 14th January 05).

7.5.3 Statistical analysis.

As discussed in section 7.2.1 the numbers of seeds in each capsule can vary considerable (Miller and Cummins 2001, Traynor 1995, Legg *et al.* 1992). However to determine the number of potential seeds in the capsules captured in the seed-traps in this study the mean of Legg *et al.* (1992) study where results from capsules collected from litter, (post-dispersal) were used. This number (2) was considered more accurate then the high numbers often given in literature, as these numbers are usually given from harvested samples collected at the beginning of the seed-shedding period and not from capsules from the peat surface or from litter. For example Traynor (1995) and Legg *et al.* (1992) harvested capsules at the beginning of September. Although using this potential number of 2 seeds per capsule may also be optimistic as Legg *et al.* (1992) suggests the number of seeds per capsules may only be half of the capsule rain.

Seed count data from the radial seed trap experiment was analysed by non-linear regression analysis (Brown 2001) to determine any relationship between numbers of *C. vulgaris* seeds deposited and the distance from the seed source.

Collected data from the radial seed trap experiment was analysed to obtain:-

1. Number of seed capsules on peat before experimental set-up.
2. Mean of seed and capsule count (m^{-2}) at each distance from seed source.
3. Seed and capsule count (m^{-2}) at each direction and distance.
4. Percentage of seeds and capsules trapped within 1m of seed source.
5. Total number of seeds (trapped seeds and seeds in the trapped capsules). A value of two seeds per capsule was assigned (see section 7.2.1 and 7.5.3)
6. Number of capsules from peat close to trap-sites.

Collected data from seed dispersal from the natural ' island' experiment was analysed to obtain:-

1. Capsule count (m^{-2}) at each distance from seed source.
2. Capsule count (m^{-2}) at each direction and distance
3. Capsules trapped within 1m of seed source.
4. Total number of seeds (seeds in capsules, n=2).

Experimental data were first tested for homogeneity of variance with Levene's test. Data from the capsule count in the seed-traps and from samples near the traps in the radial seed-trap experiment analysed by a nonparametric method, (Mann-Whitney test) using SPSS (version 13.0), to test differences in capsule quantity. An ANOVA (SPSS version 13.0) was performed on the data of the capsule count from the radial and natural island experiments, to test differences in capsule quantity. Only capsules collected on N, S, E, and W transects and sample sites 0 - 10m were included in the analysis.

7.5.4 Results.

7.5.4.1 Statistical analysis.

The results from the non-linear regression analysis showed there was no significant relationship between number of seeds and the distance at which they were trapped. Figure 7.8 shows the number of *C. vulgaris* seeds (m^{-2}) at each sampling point for the all distances from seed source. A trend line and R^2 value of 0.6147 shows that 61.5% of the 'independent' variable (seeds) can be explained by the variation of the 'dependent' variable (distance), however this was not significant.

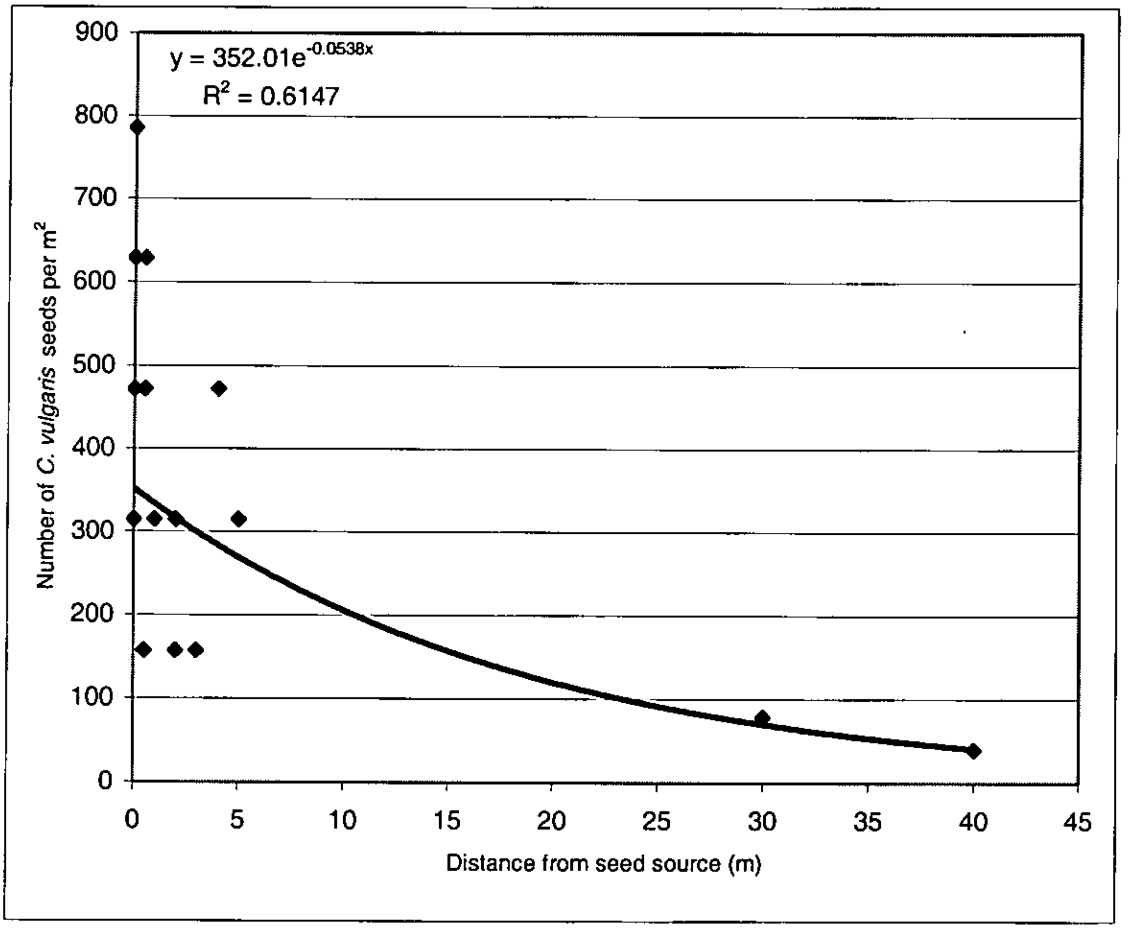


Figure 7.8 Number of *C. vulgaris* seeds (m^{-2}) at each distance from seed source. Best-fit line shows relationship between number of seeds and distance from seed source.

There was no significant difference (P>0.05) in number of *C. vulgaris* capsules collected in the seed traps and those from peat samples alongside the traps. Also there was no significant difference (P>0.05) in number of C. *vulgaris* capsules collected from the seed traps within the radial experiment and in peat samples from the island of *C. vulgaris* plants.

7.5.4.2 Radial seed traps.

No new or old *C. vulgaris* capsules were found in the peat samples removed, to allow insertion of seed traps, at the start of the experiment.

C. vulgaris seeds or capsules were trapped at most distances sampled to 40m from the seed source. However, most seeds and capsules were deposited within one metre of the seed source (73% seeds, 94% capsules) (Figure 7.9).

Capsules collected from peat samples taken from near the seed-traps were only found at 0m and 0.5m distances (Figure 7.9).

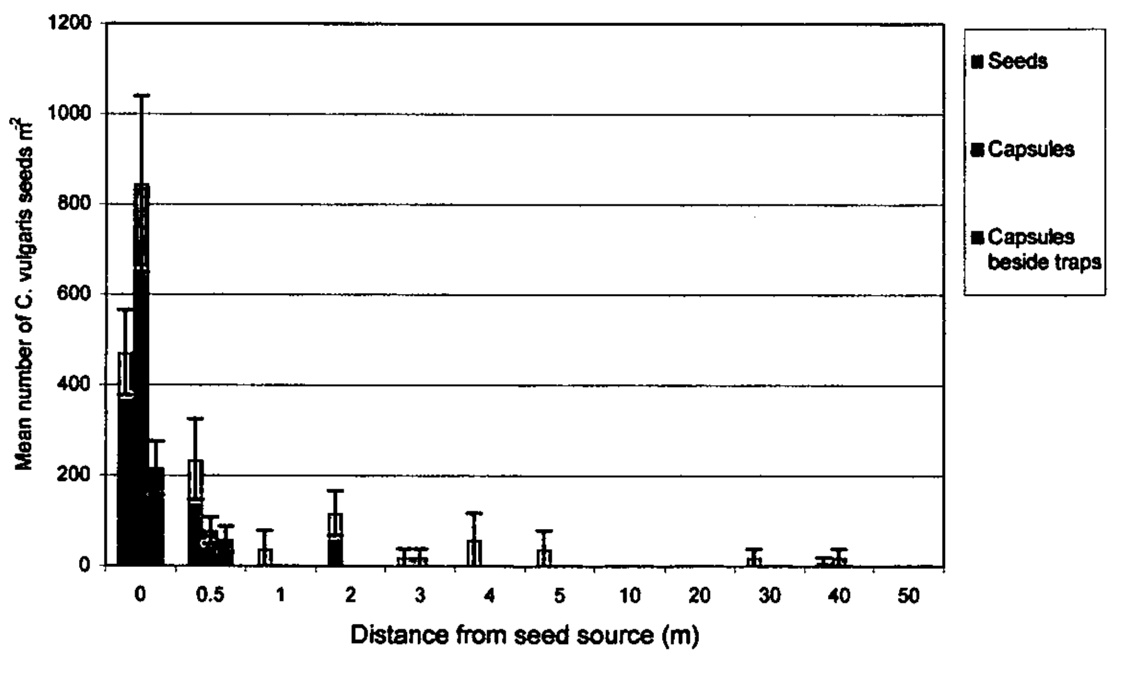


Figure 7.9 Number of seeds and capsules m^{-2} at each sampling distance from central translocated *C. vulgaris* plants in radial seed-trap experiment, (Data mean ± SE, n=8, 0-10m: n=4, 20-50m).

7.5.4.3 Direction and quantity of trapped *C. vulgaris* seeds..

Only on the north transect were seeds and capsules trapped at more than 5m from seed source with 40m the maximum distance for seed dispersal. (Figure 7.10).

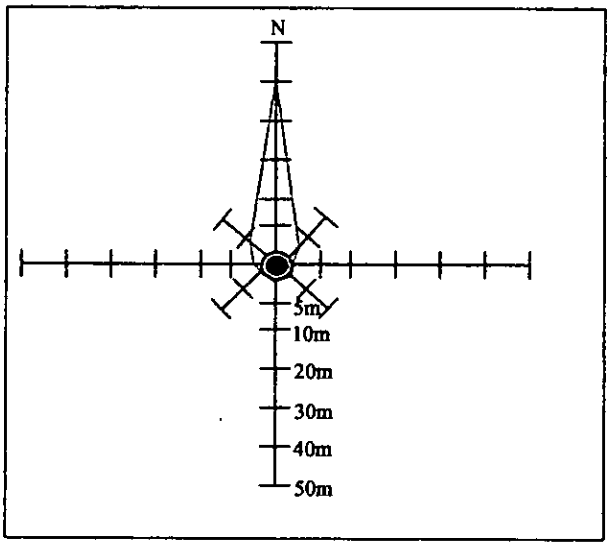


Figure 7.10 Maximum deposition distances of *C. vulgaris* seeds and/or capsules from the central transplanted *C. vulgaris* plants.

Highest number of seeds trapped was on the south-east (1,572m^{-2}) at 0m. Number of seeds trapped at 40m, the maximum distance, was 39m^{-2}. The maximum distance for removed capsules was 3m when 157m^{-2} were trapped. When the potential numbers of seeds (n=2) in the capsules were included in the count, the highest calculated number of seeds was 3616 m^{-2} on the south-east transect. (Table 7.0 and figure 7.11).

Table 7.0 Number of *C. vulgaris* seeds and capsules (in brackets) m^{-2} for each transect and distance from seed source in the radial seed-tapping experiment. [] = Total number of seeds (seeds + seeds in capsules n=2 seeds).

Distance from seed source (m)	N	NE	E	SE	S	SW	W	NW	Mean
0	472 (1100) [2672]	472 (1100) [2672]	314 (1415) [3144]	472 (1572) [3616]	943 (472) [1887]	472 (786) [1344]	0 (314) [628]	629 (0) [629]	471 (845) [2198]
0.5	472 (0) [472]	157 (157) [373]	0 (0) [0]	472 (157) [686]	0 (157) [314]	157 (0) [157]	0 (157) [314]	629 (0) [629]	236 (76) [368]
1	0 (0) [0]	0 (0) [0]	0 (0) [0]	314 (0) [314]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	39 (0) [39]
2	314 (0) [314]	314 (0) [314]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	157 (0) [157]	157 (0) [157]	117 (0) [157]
3	157 (0) [157]	0 (157) [314]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	20 (20) [59]
4	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	472 (0) [472]	59 (0) [59]
5	314 (0) [314]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	39 (0) [39]
10	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]	0 (0) [0]
20	0 (0) [0]		0 (0) [0]		0 (0) [0]		0 (0) [0]		0 (0) [0]
30	79 (0) [79]		0 (0) [0]		0 (0) [0]		0 (0) [0]		20 (0) [20]
40	39 (0) [39]		0 (0) [0]		0 (0) [0]		0 (0) [0]		10 (0) [10]
50	0 (0) [0]		0 (0) [0]		0 (0) [0]		0 (0) [0]		0 (0) [0]

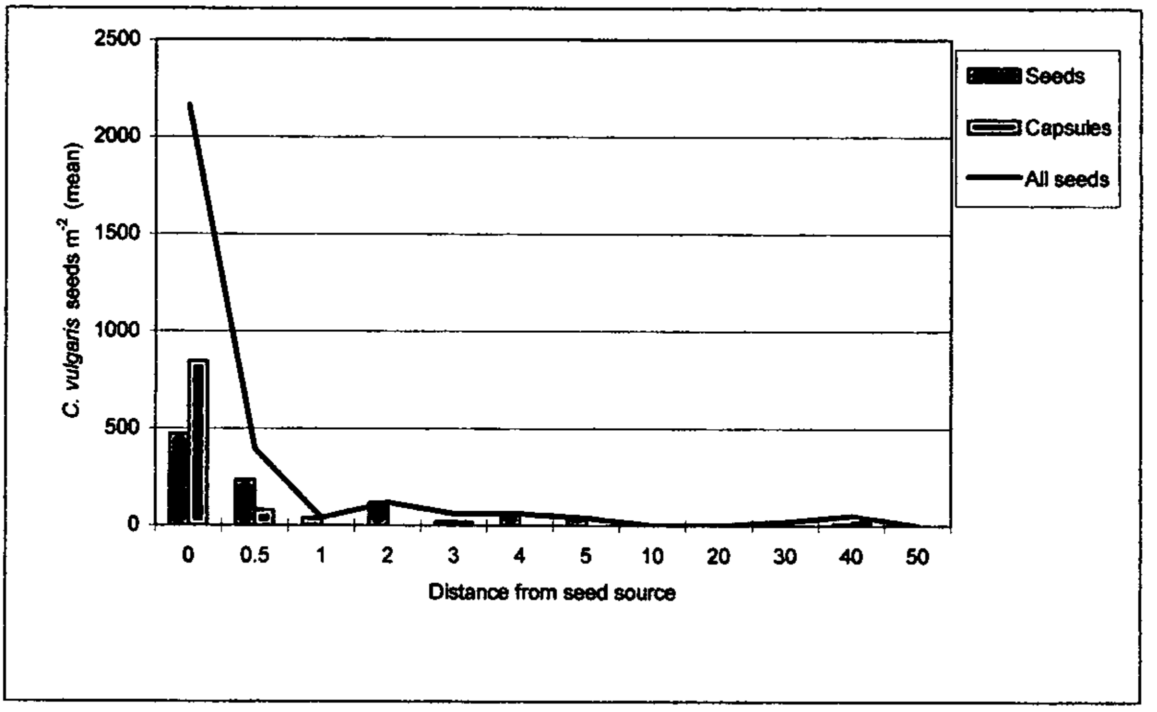


Figure 7.11 Seed count per distance from seed source when two seeds per capsule are included in the calculations (green line) within the radial seed trapping experiment.

7.5.4.5 Capsule dispersal from a natural 'island' of *C. vulgaris*.

All *C. vulgaris* capsules collected from peat samples were found within 1m of the seed source. Capsules were trapped on all transects but not at all distances, (Table 7.1).

The maximum mean number of potential *C. vulgaris* seeds (n=2) in the trapped capsules was 943m^{-2} at 0m from seed source (Figure 7.12).

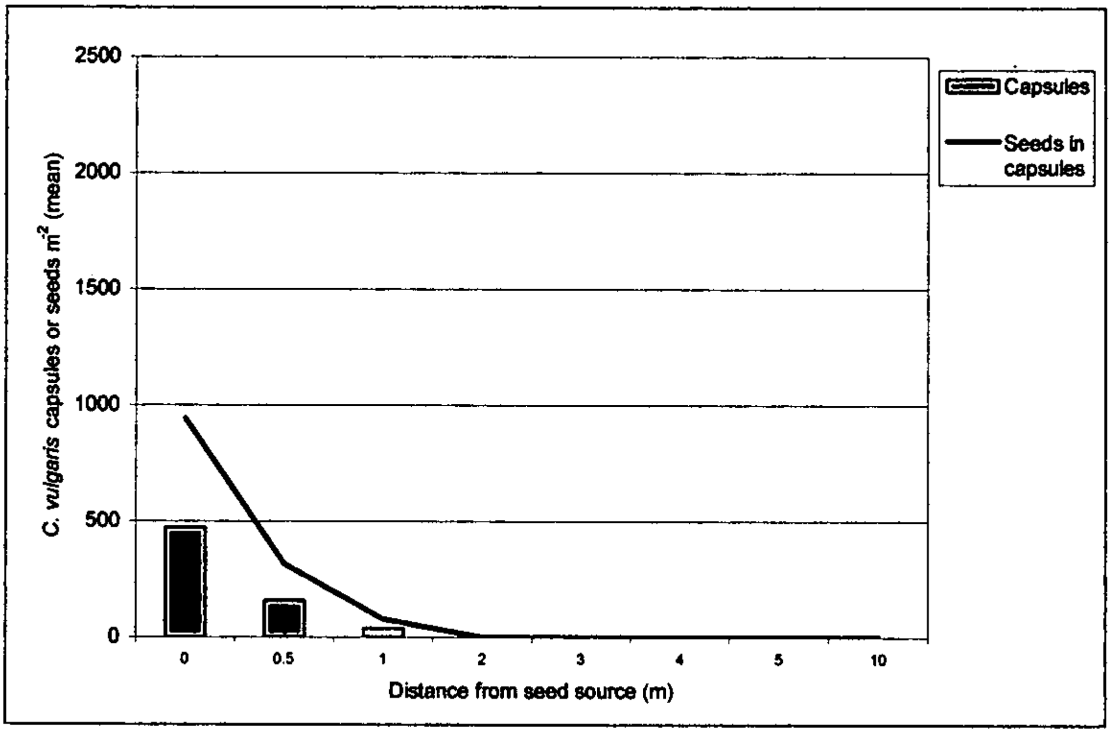


Figure 7.12 Number of *C. vulgaris* capsules and seeds within (n=2), (green line) from the natural *C. vulgaris* 'island' experiment.

Table 7.1 Number of *C. vulgaris* capsules m^{-2} per transect and at each distance from seed source (natural 'island' of *C. vulgaris*). No capsules were collected at any distance >1m from seed source.

Distance from seed source (m)	North	East	South	West	Mean
0	157	786	472	472	472
0.5	0	314	314	0	157
1	0)	0	0	157	39

7.6 *CHAPTER DISCUSSION.*

7.6.1 Linear seed-trap experiment

Year one seed trap design experiment showed that it was possible to trap *C. vulgaris* seeds during the seed-shedding period in upland moorland devoid of all vegetation. Result from this initial experiment showed seeds were trapped to 35m but most were located within the first metre from the seed source (57% seeds, 76% capsules). There was no association between seed numbers and distance from seed source, which may be due to the linear design of this experiment that did not take account of any environmental conditions, such as wind direction; these were addressed in subsequent experiments.

7.6.2 Radial seed-trap experiment

With the second seed-trapping experiment a buffer zone (with no *C. vulgaris* plants) was needed around the experimental site, therefore the maximum distance that seeds could be trapped was 50m. This experimental design was similar to that used by Bullock and Clark (2000), although maximum distance of transects was shorter and fewer traps were used. The design also ensured that all samples could be collected in one day, as poor weather conditions often limited site access. However, this restricted the distance at which the seeds could have been trapped, the maximum distance at which seeds were trapped (45m) being less than that reported by Bullock and Clark (2000). As with the linear experiment most seed (73%) and capsules (94%) capsules were collected within the first metre from seed source, this was also observed by Bullock and Clark (2000).

No capsules, old or new, were found in peat samples removed from the research site prior to seed trap insertion. This result suggests capsules were not reaching or staying on site and therefore seedbank and litter accumulation away from established vegetation was not occurring. These data are also supported by results from Chapter 5, where germination and growth from natural seed-rain was not recorded on peat samples from the Stalybridge site. The result may also suggest that seed-shedding had not commenced at the start of this experiment. Also numbers of seeds, except within 1m of seed source, were below those used in moorland management post wildfire (Anderson 2004).

Although data of wind direction and speed were not recorded, results suggest that the spread of the seeds was very directional and seed dispersal would be greatly influenced by wind speed and direction (Figure 7.8), which was reported by Bullock and Clark (2000). The maximum distance of seeds and capsules dispersal were 45m, which occurred on the northern transect. However, most seeds were deposited on the south, southwest and southeast but all within 1m of seed source. This dispersal pattern suggests seeds are being released from the capsules on plant recoil when strength of wind is suddenly reduced.

Although the experimental results from this study are similar and follow the same trend to those observed by Bullock and Clark (2000), there are a number of differences. Less seed within the first metre were recorded in this study, 73% in comparison to 91% in their study. The number of *C. vulgaris* seeds trapped were also lower that those reported by Bullock and Clark (2000) and by Barclay-Estrup and Gimingham (1994) who suggested, for example that 169,010m^{-2} seeds are deposited in the building phase of *C. vulgaris* plants. Traymor (1995) also suggested the productivity of *C. vulgaris* to be 880,000 m^{-2} although this was on a lowland heath. There may be a number of explanations for these differences. Bullock and Clark's (2000) study was in lowland grassland and Nathan and Muller-Landau (2000) and Bullock and Moy (2004) have shown that plants may act as seed traps. Therefore, *C. vulgaris* seeds and capsules in this study may have been removed further from the parent plant, as there was no vegetation or other barriers to interfere with wind velocity and increase deposition of seeds (Legg *et al.* 1992). This is also illustrated in the trial seed-trap experiment where only 57% of seeds were trapped within 1m of the seed source.

Seeds may also have been removed from site by wind and/or water; Fagundez and Izco (2004) suggest small elliptical seeds like *C. vulgaris* are easily removed from site. Although capsules may still have been present on the *C. vulgaris* plants ready for dispersal latter in the seed-setting period (Gimingham 1972), this was not the case, as on the last sample collection date (14th Jan. 05) the relocated plants were examined and very few capsules remained. Environmental conditions and location of site may also influence seed-setting capability of *C. vulgaris* plants (Cummins and Miller 2002). Size of seed source may have influenced the numbers of seeds trapped, which is illustrated in the trial experiment where large stands of *C. vulgaris* were used as the seed source

(Figure 7.4) and more seeds were trapped. However, numbers of capsules trapped in the natural island seed traps were not significantly different from the radial traps.

The implications of these results are, as suggested by Radley (1965) and Maltby *et al.* (1990), that natural vegetation regeneration will be slow. Although *C. vulgaris* seeds have been shown to be dispersed 45m into the bare site, the number of seeds is well below those reported by other studies (Bullock and Clark 2000, and by Barclay-Estrup and Gimingham 1994). Although *C. vulgaris* is generally classified as an r-strategy species with a large numbers of seeds and good recolonisation potential these results suggest this is not the case in upland moorland post wildfire.

Results suggest dispersed seeds do not remain on site; this would also apply if the seeds were from post-wildfire management. Therefore *C. vulgaris* seeds should not be spread unless is adequate protection is provided. A change in environmental conditions on a burnt moor may aid germination of *C. vulgaris* seeds. This was seen at the Stalybridge site where erosion of peat down to the underlying mineral surface leaving an uneven surface may have provided 'safe-site' for *C. vulgaris* seeds with all the requirements for germination and establishment of seedling (Harper 1977).

In conclusion, results suggest seeds and capsules are either remaining close to the parental plant or are being removed from site. Numbers of seeds and capsules collected from the bare peat or within the traps further than 1m from seed source did not reach the numbers recorded by other authors. This suggests natural regeneration and potential post-wildfire management may be hindered by lack of *C. vulgaris* seeds on unprotected burnt moorland.

8.3 *IMPLICATIONS FOR MANAGEMENT.*

This research suggests post-wildfire management of using a nurse species in addition to lime and fertiliser can facilitate the regeneration of *C. vulgaris* on a severely burnt moor. Regeneration of *C. vulgaris* post-wildfire has also been seen on other upland moorland, for example, the North York Moors (NYMNPA 2003, Pickering 2007). However, vegetation cover was shown to be more likely to occur where the peat is shallow than on deep peat. The nurse species will decline but may still have a substantial cover (20%) ten years after the fire. Other early colonising plant species, for example *Polytrichum spp,* may increase cover over this period and may become problematic; suggesting monitoring of the regenerating site should be an integral part of post-wildfire management. The full site surveys of Darwen Moor also showed that colonising plant species on the burnt section were also migrating into the unburnt section, this is illustrated by an increase in *Polytrichum spp* cover suggesting post wildfire vegetation monitoring should not be confined to the burnt sections of moorland.

Due to poor immigration and germination rate of *C. vulgaris* seeds on bare moorland, regeneration should not be left to natural processes. Nurse species or other method to provide adequate long-term protection for *C. vulgaris* seeds must be established before any application of *C. vulgaris* seeds as this research strongly suggests that *C. vulgaris* seeds should never be applied to bare peat. Without adequate protection an application of *C. vulgaris* seeds is a waste of resources. Bales of heather, as used on Darwen Moor and spread by volunteers on to bare peat, may have been a more advantageous management tool if they had been placed on the moor as a wind-break, providing protection for the sown nurse species and immigrating *C. vulgaris* seeds.

Applying post-fire management to small areas, within a large burnt area, may seen ideal, from which the vegetation by way of seeds and vegetative could slowly advance filling the gaps (Miles 1979). However, small areas may become susceptible to damage from deposits of peat from wind and/or water erosion. This was demonstrated on the Stalybridge site when the polyacrylamide gel experiment was destroyed in one storm (section 6.5.3) suggesting whole site management is preferable.

One method that maybe implemented to enhance environmental conditions on moorland is to block drainage ditches thereby raising the water table, increasing the water content of the peat and reducing potential water erosion. Such work is often undertaken after revegetation management and it is suggested that it ought to be one of the first post-wildfire management techniques applied. Neither research site in this study (2007) have received such management, although the managers on Darwen Moor are now considering it. The Stalybridge site shows the damage from water erosion (section 2.4).

Given the findings from this research and all available material from the scientific literature: the following is a recommended management sequence for a large burnt section of upland moorland and where money is not an issue.

1. Adequate resources to react quickly to damaged site and to apply appropriate management before peat erosion or exposed surfaces becomes hard or mobile.
2. Access denied to sheep, thus protecting any management and establishing vegetation.
3. Blocking of drainage ditches, reducing run-off, and potential erosion.
4. Peat protection management, for example nurse species or geo-textiles.
5. Application of *C. vulgaris* seeds once nurse species is established or other peat protection is in place.
6. Monitoring of site and the ability to react quickly if management is failing in part of site, or undesirable plants are colonising

8.4 *METHODOLOGY*

Results from Chapter 3 suggested collection of data by a photographic method was an acceptable but unconventional method to use on upland moorland, although this method is supported by Dietz and Steinlein (1996). Monitoring the permanent quadrats by point quadrat and photography over four years also confirmed the value of photography in vegetation survey with no significant differences between this and the point quadrat method. Photography also enabled the images to be archived and re-examined when grass species identification became problematic (section 4.3.1).

Photography was also used to collect data from the polyacrylamide experiment (section 6.4), with percentage cover calculated by counting pixels; this proved a simple method as there were only two colours (grass and peat) in the calculation.

Marking the permanent quadrats with metal pegs, to be found by grid reference, eye and metal detector enabled quadrats to be undisturbed throughout the research period in an area that is extensively used by the general public. This method also showed robustness with some quadrats surviving muirburn. This method may also enable surveys of the permanent quadrats to be undertaken over numerous years.

The method for protecting the sample sites using a polyacrylamide gel at the Stalybridge research site (section 6.4.3.) may have influenced the results, as the chicken-wire and the stones used to hold it in place also provided protection from the wind and rain. This method was considered the best possible way of protecting the site from sheep as fencing the sample sites was not an option due to inaccessibility. Destruction of the first experiment, due to mobile peat being washed and blown in, showed how environmental conditions can affect management on these moorland sites. However, results may also demonstrate a need for peat protection on site before vegetation regeneration can be achieved.

Seed trap design was similar to those used in previous research with only a small adaptation but these proved robust enough for sample collection on an open moor. Results were expressed as seeds m^{-2}, although this is unconventional as most research use seed-shadows to depict dispersal range. Nevertheless, it allowed comparisons with seed application rates used in management.

The use of bioassays in a growth cabinet with controlled environmental conditions allowed plant growth to be assessed without chemical analysis of the peat, which may or may not have shown the potential growth of *C. vulgaris* on the burnt peat.

8.5 *FUTURE RESEARCH*

Based on the finding of this research, some suggestions for future research are proposed.

Whilst the permanent quadrats results failed to show any significant change or direction of vegetation change the experiment has great potential. The metal markers used to mark the permanent quadrats, and using GPS with the gird references, mean these quadrats could continue to be monitored for many years. This would establish rate of *C. vulgaris* regeneration and vegetation succession following post-wildfire management of liming, fertilising and application of grass species. Any long-term problems with dominance or introduction of undesirable plant species could be monitored and suitable corrective management applied. Also factors that may be limiting succession could also be investigated.

An investigation into the survival of *C. vulgaris* in drought conditions would show the true potential of *C. vulgaris* seeds to disperse from the parental plant, survive the harsh conditions of the bare peat post-wildfire, increase the seed bank or germinate when adequate environmental conditions were available.

Use of polyacrylamide gel may be another method that needs more investigation. It is relatively inexpensive, simple to administer and may provide the environmental conditions needed for rapid establishment of nurse species. It may also be suitable for use in conjunction with other methods of management, for example geo-textile, brash or other form of peat protection. Other methods of protection that provide 'safe sites' could also be investigated, as litter, rocks and logs have all been shown to provide safe sites with an increase in germination, survival and growth of plants (Cargill and Chaplin 1987, Smit *et al.* 2005). A factorial experiment could be used to explore the potential of these methods in providing adequate protection for germination of *C. vulgaris* or nurse species.

Another question that may need answering is:- did it help that Darwen Moor was not a well-managed site before the wildfire? This may have allowed invasion/colonisation from the unburnt and surrounding rough grassland, whereas the Stalybridge site had only a *C. vulgaris* dominated vegetation on a muirburn-managed site?

The aims of this thesis have been addressed; *C. vulgaris* regeneration has been demonstrated as attainable from established post-wildfire management techniques. Some reasons for the slow vegetation colonisation from natural regeneration on moorland post-wildfire have been presented, in addition to a recommendation for future management. However, results also show the complexity of factors limiting regeneration and that further research is still required.

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Appendix 1. Stalybridge site survey results.

Vegetation survey

A vegetation survey was completed in 2000, with quadrats (0.25m) sampled every 5m on a transect across the site (n=35). Data was collected by digital photography, and the mean percentage vegetation cover calculated as discussed in Chapters 3 and 4. Due to planned remedial management the second survey was completed in 2004.

The results from the 2000 survey showed the cover on the Stalybridge research site to be 69% bare peat, 9% grass *spp.* and 22% *C. vulgaris*. Four years later the cover was 77% bare peat, 6% grass and 17% *C. vulgaris*. This increase in bare peat and reduction of vegetation cover was due to a 2003 wildfire which burnt all the surrounding moorland and part of the fenced research site. There were no bryophytes or lichen on the bare eroding peat.

Appendix 2. Evidence for using Adobe-Photoshop to correct picture-warp on images of quadrats.

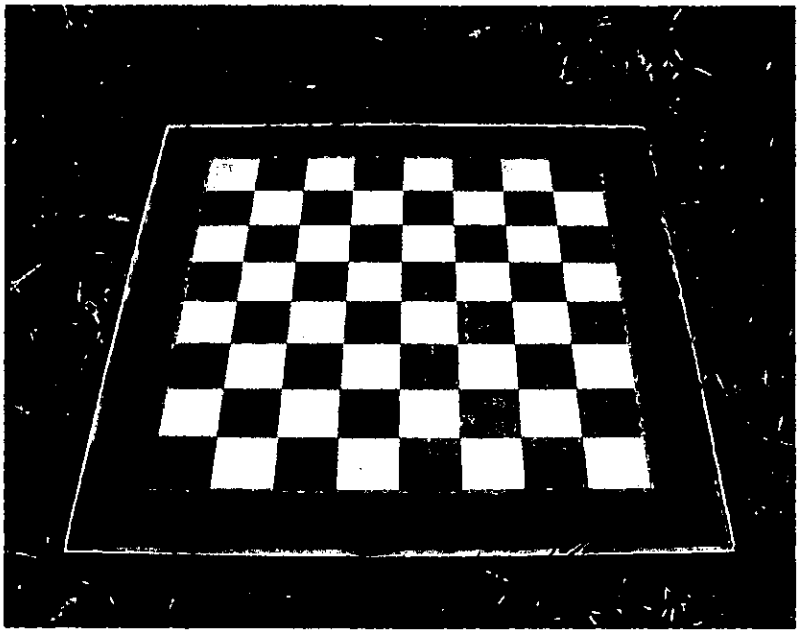


Figure App 2.0 Image of chess-board showing picture-warp.

The above image (Figure App 2.0) shows picture-warp from poor camera angle (not directly above object) or uneven ground. A chess-board was used to show perspective is correct and proportion of area is unaltered when image is malipulation and corrected.

Using Adobe-photoshop (version 9) the following proccedure was used. First open image, then select crop tool and drag over part of image required. Ensure that the 'perspective box' on top tool bar is 'ticked'. Using the marquee tool move to each corner of required section of image by placing pointer inside the corner handles (bound box) and dragging. Then tick the crop box on tool bar and on the drop down dialog box select 'crop'.

Resize image by selecting image on top tool bar. Select image size and adjust the width and height to the same pixel count, then click OK. The image is then ready to superimpose with grid and calculation of vegetation cover can be made. (Figure App 2.1).

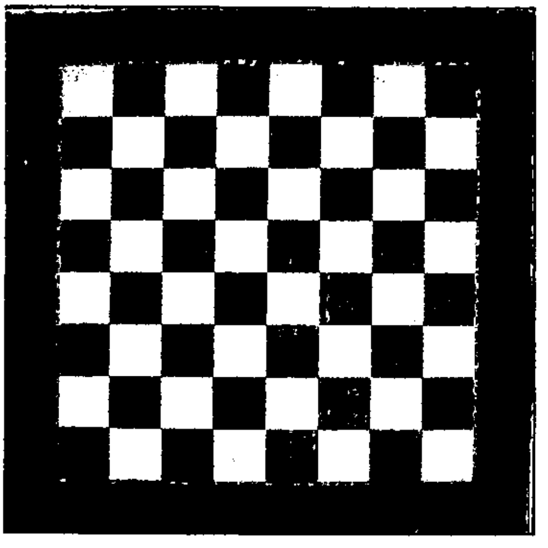


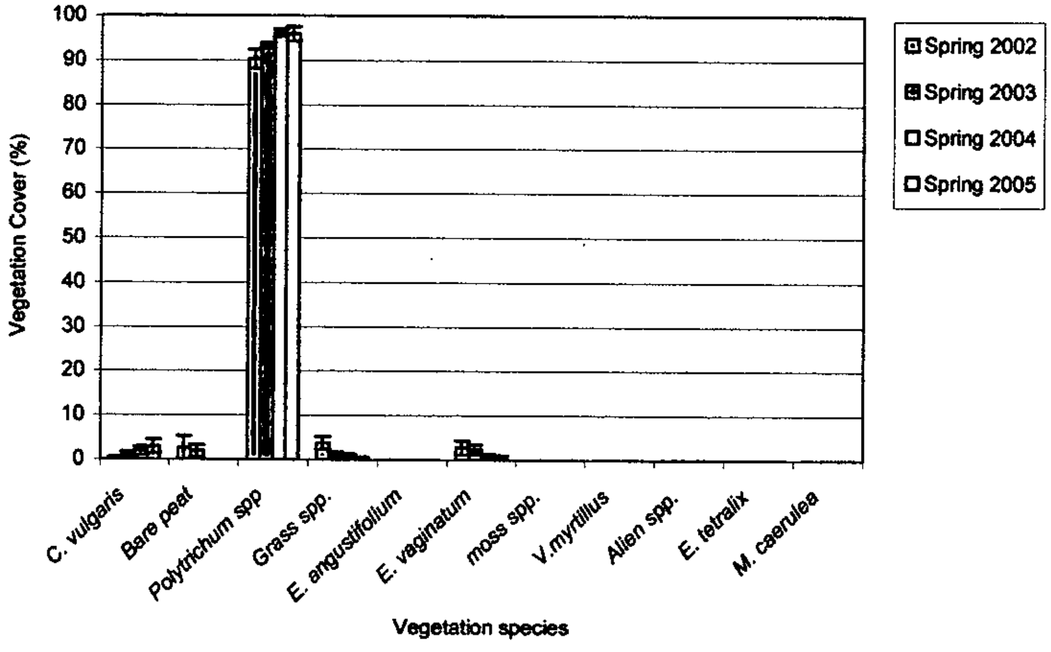
Figure App 2.1 picture-warp removed keeping perspective correct.

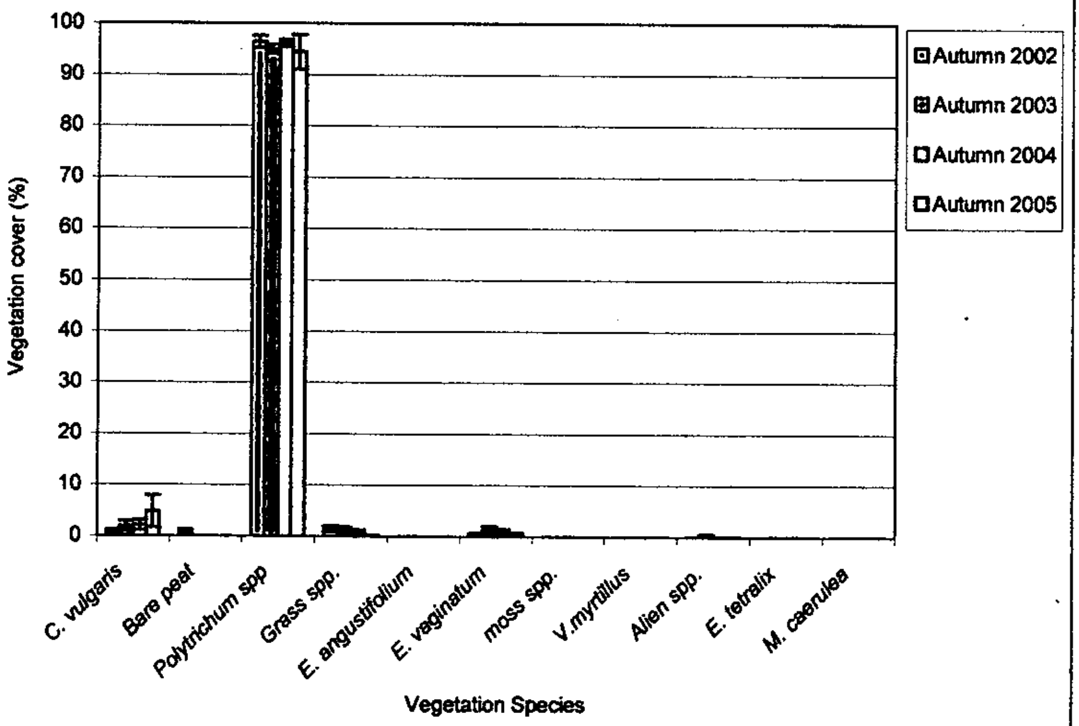
Appendix 3

Grid references for the permanent quadrats set out on Darwen Moor.

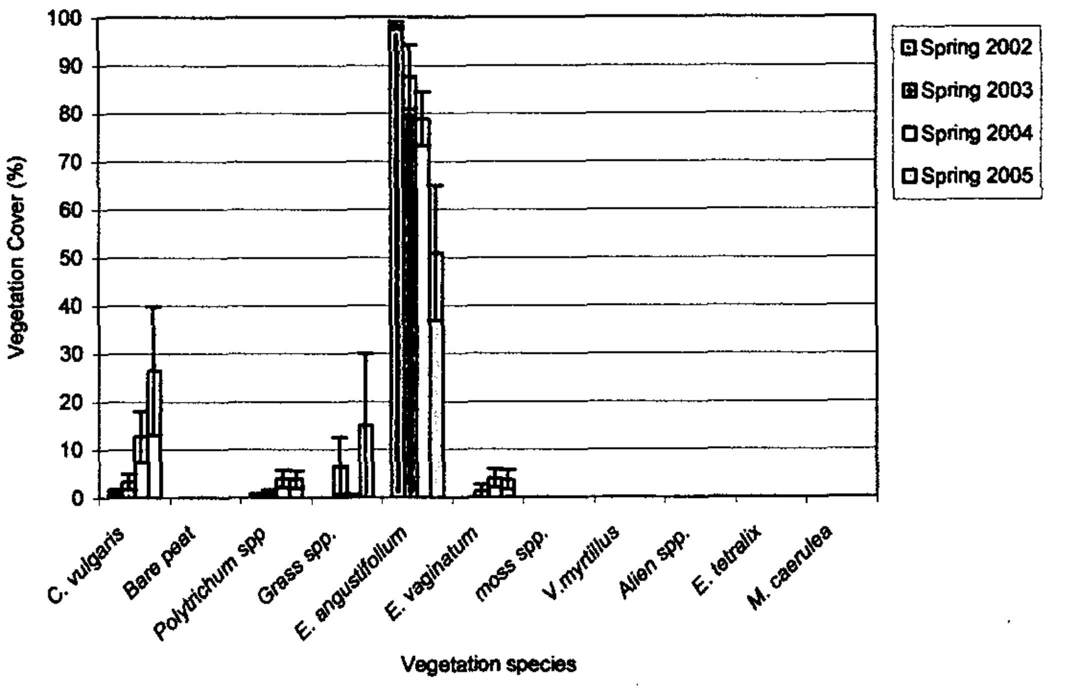
Quadrat	Grid Reference				Quadrat	Grid Reference		
1	SD	68065	20922		37	SD	68083	20908
2	SD	68177	20772		38	SD	68099	20917
3	SD	68273	20821		39	SD	67969	20907
4	SD	68268	20848		40	SD	67980	20923
5	SD	68310	20816		41	SD	67781	21384
6	SD	67826	21265		42	SD	67806	21383
7	SD	68132	20833		43	SD	68009	20762
8	SD	68297	20838		44	SD	67980	20835
9	SD	68123	20875		45	SD	68020	20881
10	SD	68227	20781		46	SD	67762	21406
11	SD	68075	20812		47	SD	67765	21392
12	SD	68206	20758		48	SD	67803	21297
13	SD	68020	20727		49	SD	67830	20731
14	SD	67997	20902		50	SD	68216	20900
15	SD	68110	20865		51	SD	67823	21030
16	SD	68157	20773		52	SD	68137	20843
17	SD	68223	20767		53	SD	67970	20939
18	SD	68280	20792		54	SD	67650	21117
19	SD	68010	20737		55	SD	67550	21141
20	SD	68037	20743		56	SD	67552	21140
21	SD	68061	20775		57	SD	67508	21129
22	SD	68109	20848		58	SD	67501	21170
23	SD	67842	21245		59	SD	67731	20596
24	SD	67789	21393		60	SD	67804	20655
25	SD	67737	20630		61	SD	67767	20709
26	SD	67764	20690		62	SD	67815	20712
27	SD	67694	21007		63	SD	67763	20669
28	SD	67839	21013		64	SD	67817	20656
29	SD	67631	21132		65	SD	67869	20690
30	SD	67615	21099		66	SD	67737	20942
31	SD	67931	20875					
32	SD	67947	20871					
33	SD	67977	20885					
34	SD	67832	21207					
35	SD	67785	21204					
36	SD	67720	21195					

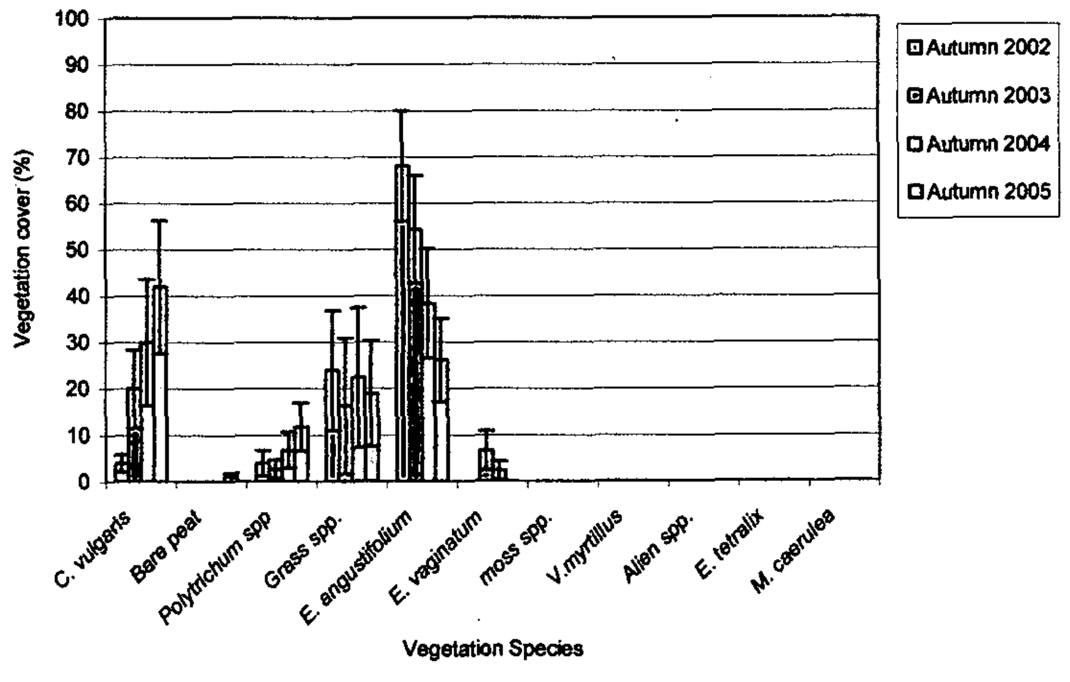
Appendix 4 – Change of vegetation cover within each sub-community on Darwen Moor, data collected from permanent quadrats.



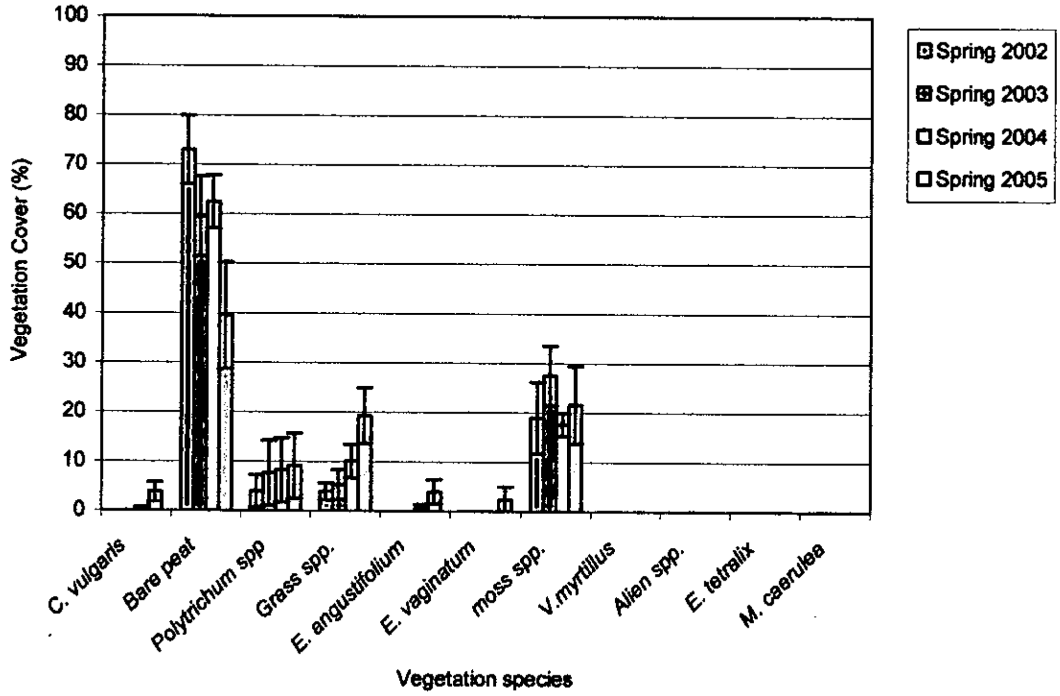


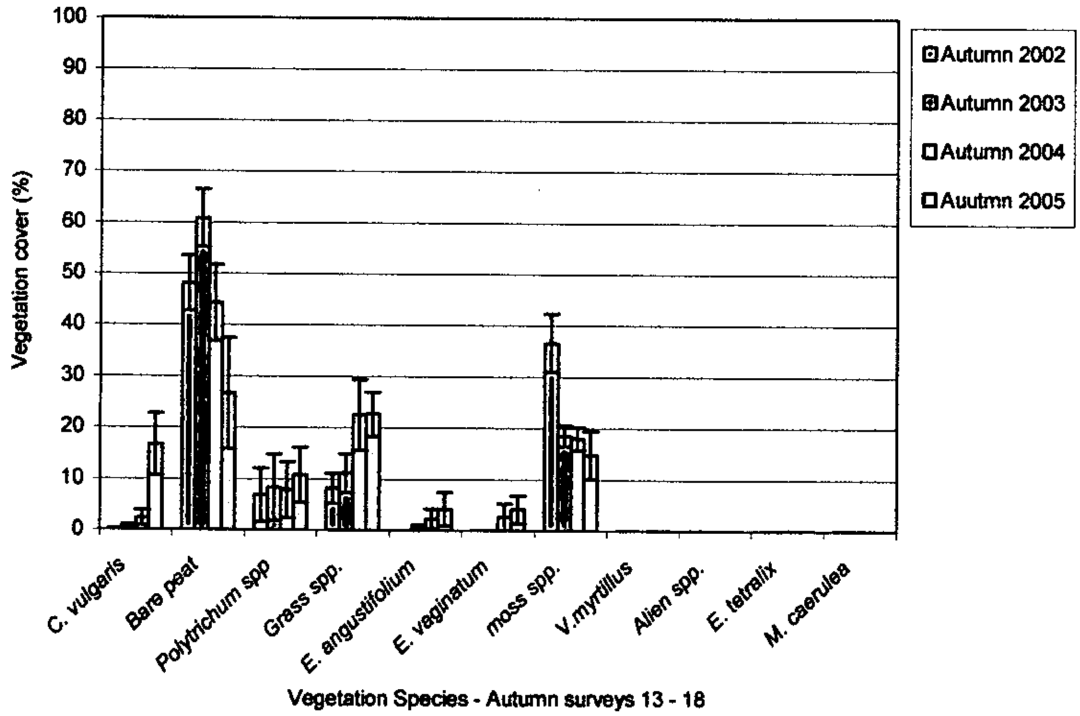
Quadrats 1-6 *Polytrichum spp*. Sub-community



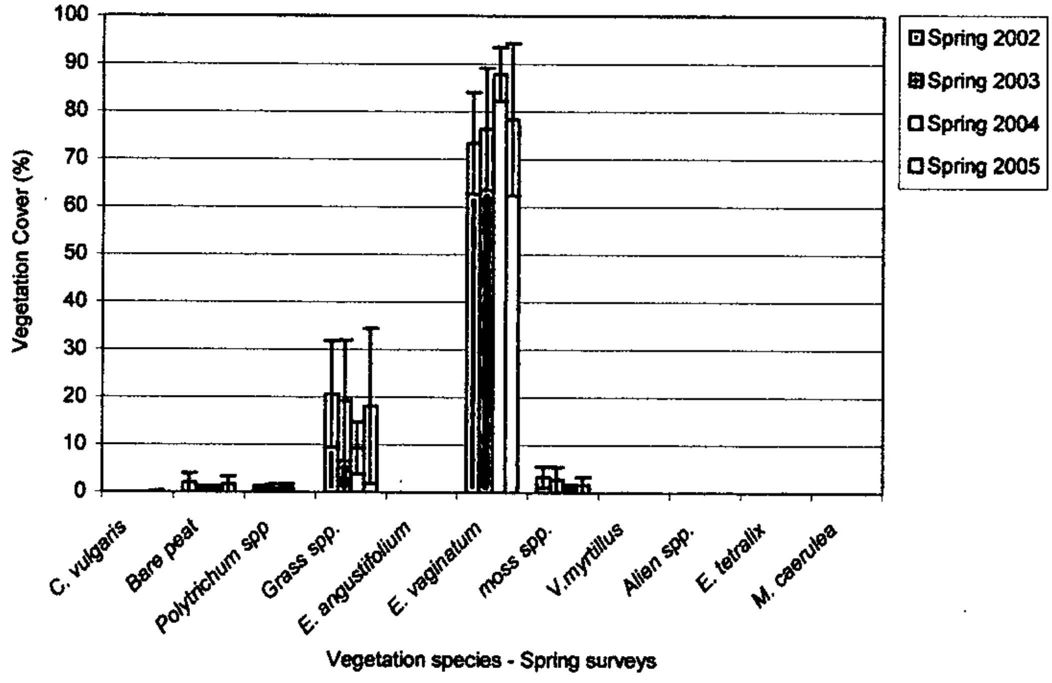


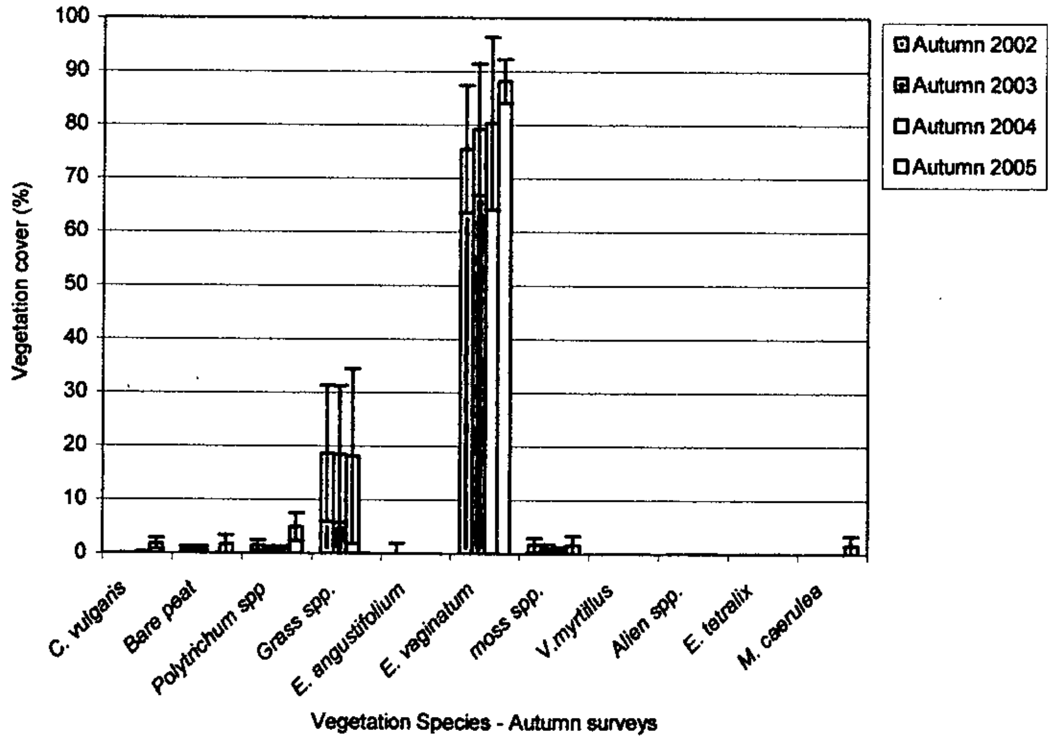
Quadrats 7-12. *E. angustifolium* sub-community



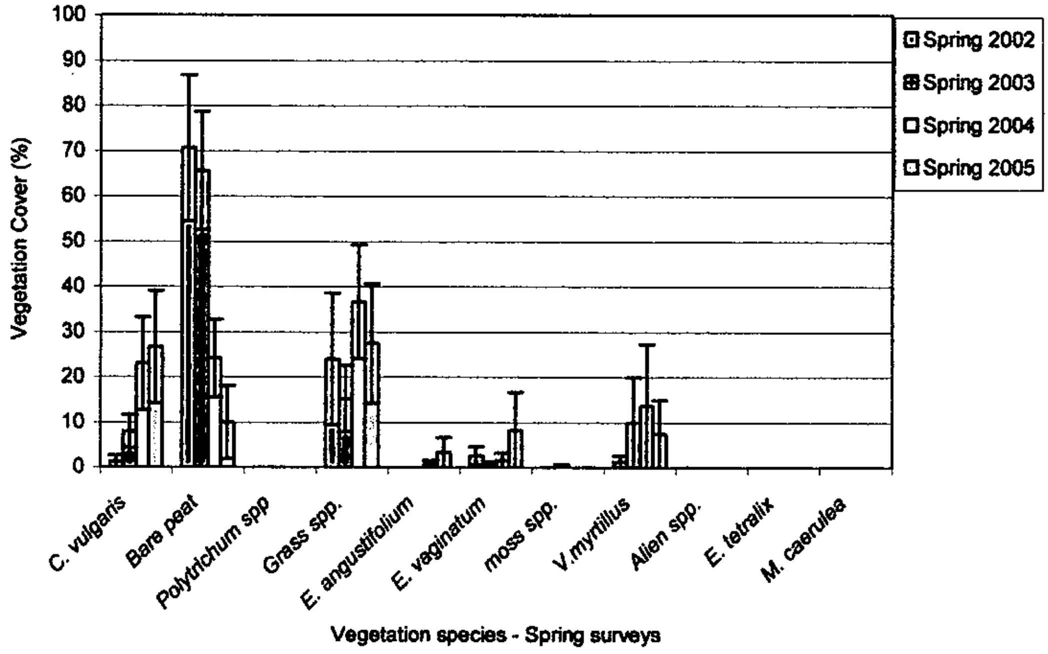


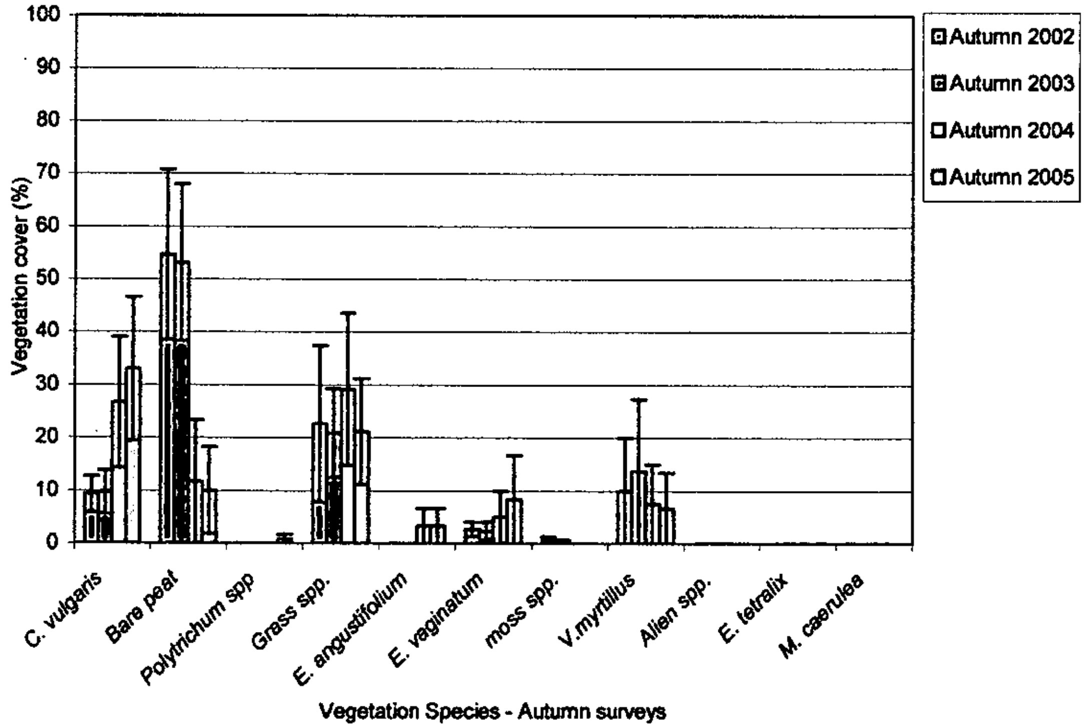
Quadrats 13-18 Bare peat, moss species sub-community



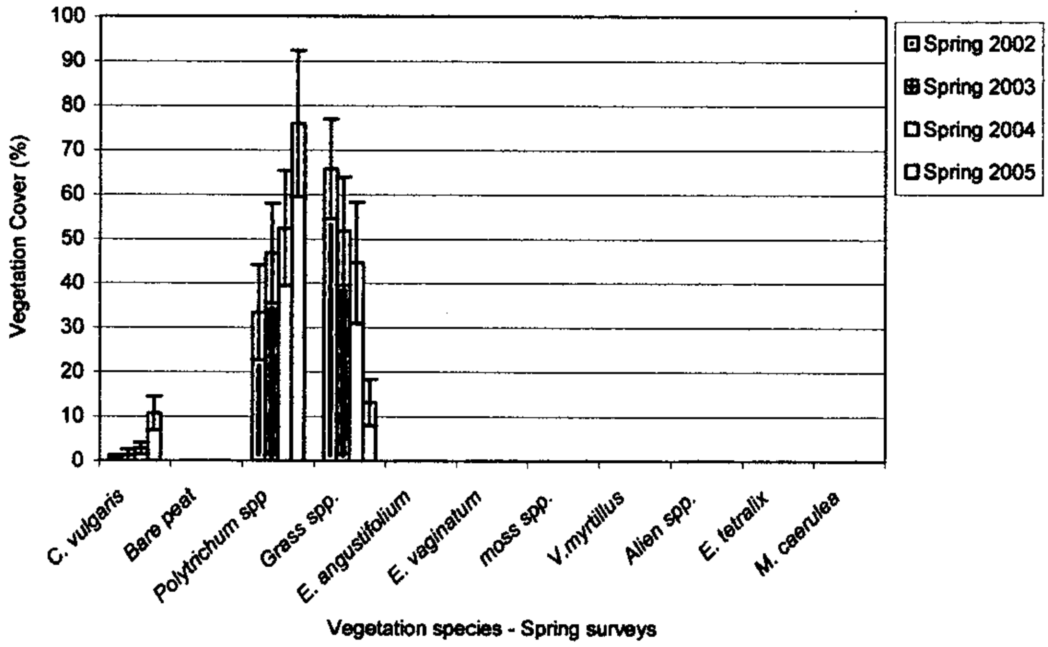


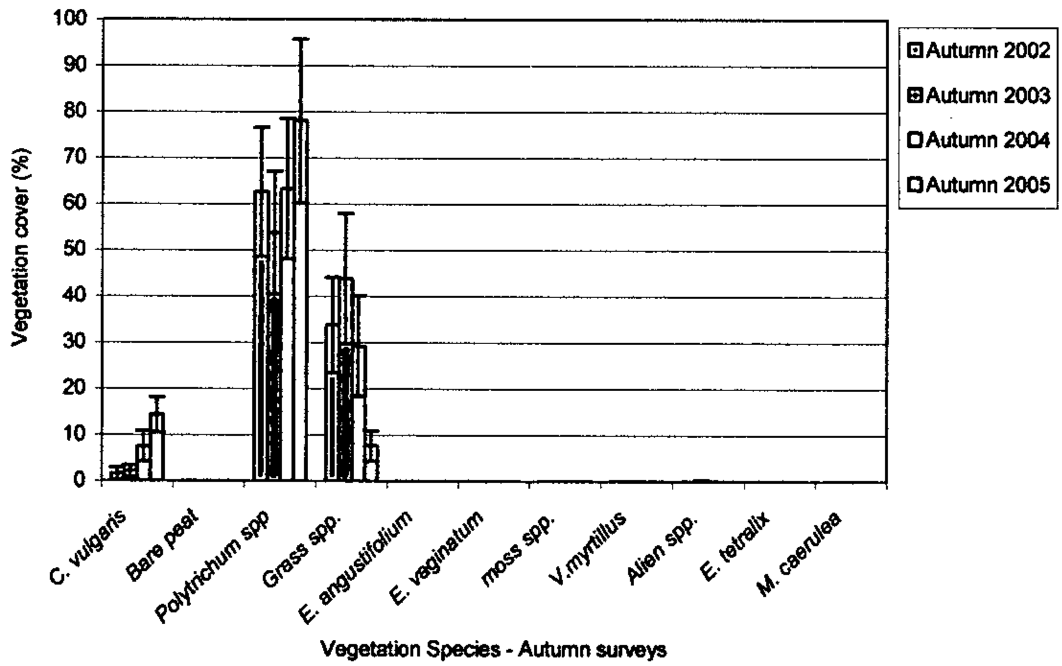
Quadrats 19-24 *E. vaginatum* sub-community



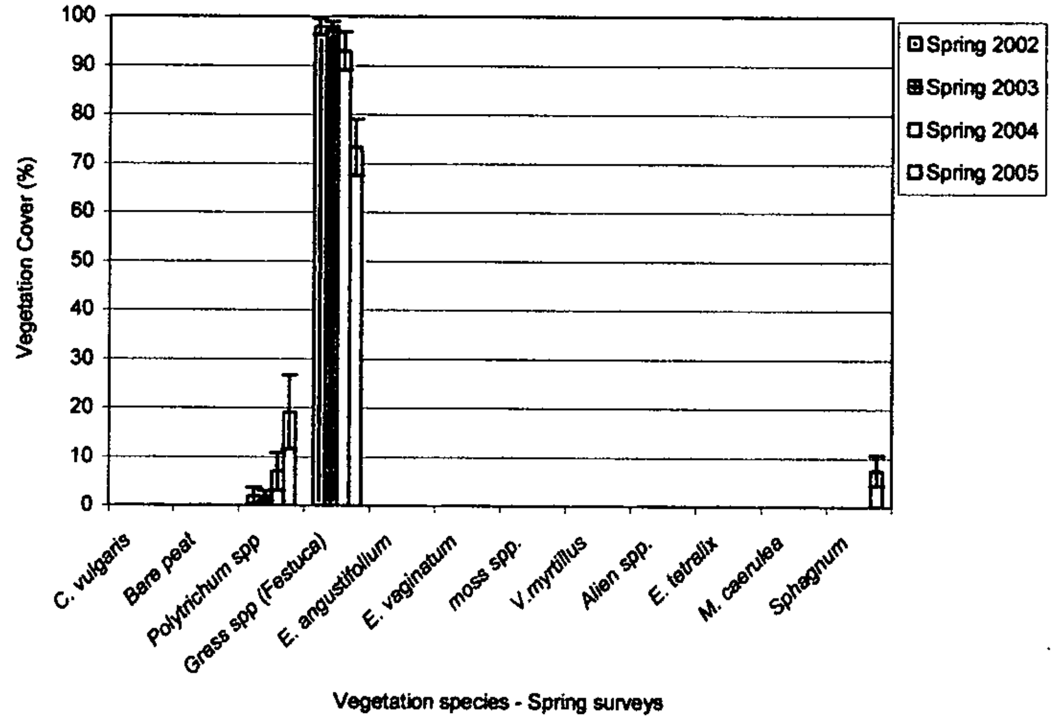


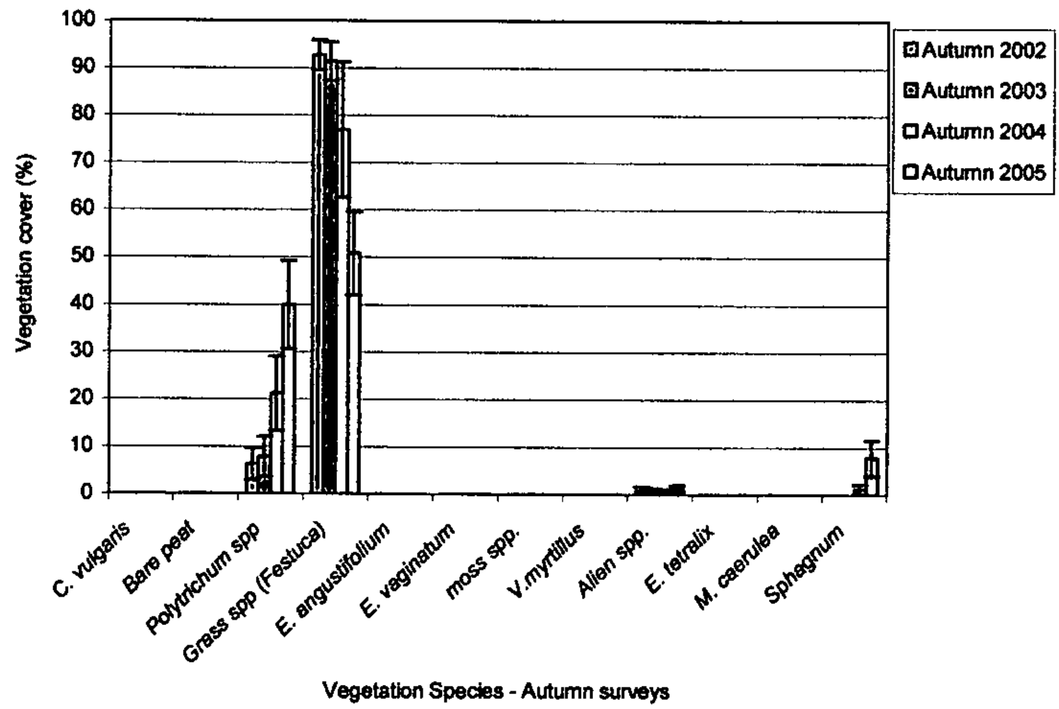
Quadrats 25-30 *Burnt C. vulgaris, V. myrtillus* sub-community



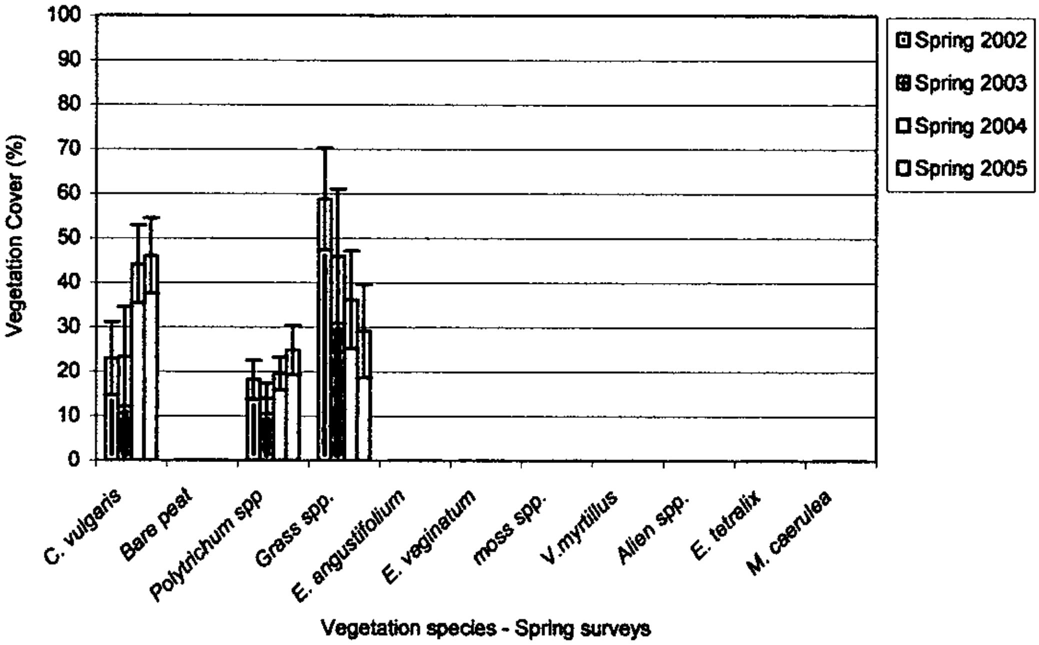


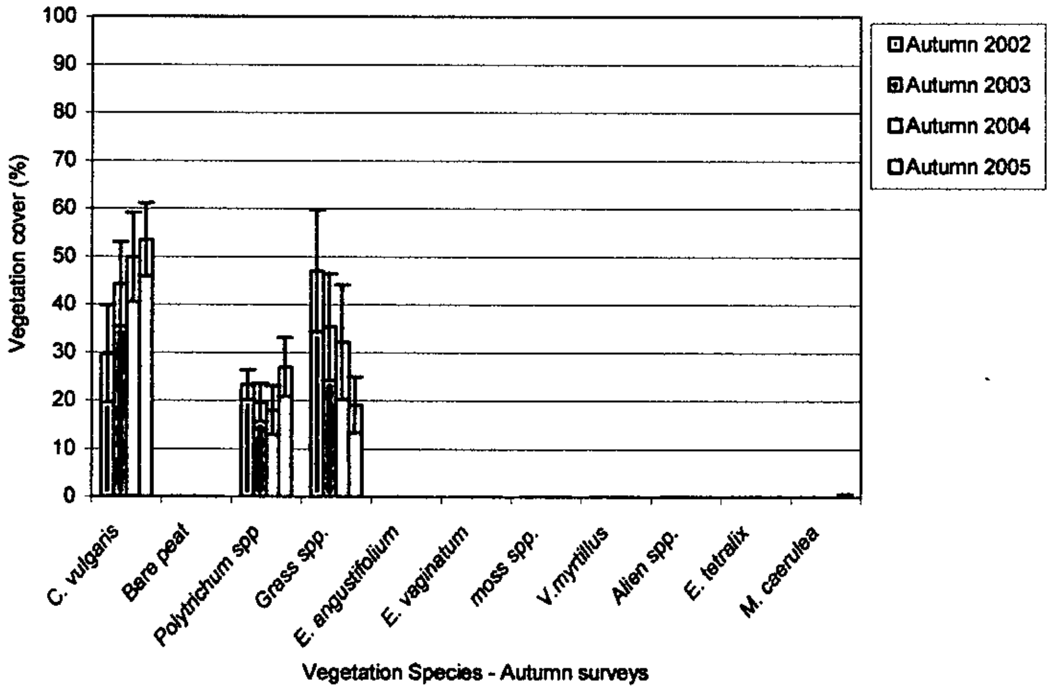
Quadrats 31-36 *Polytrichum sp., D. flexuosa* sub-community.



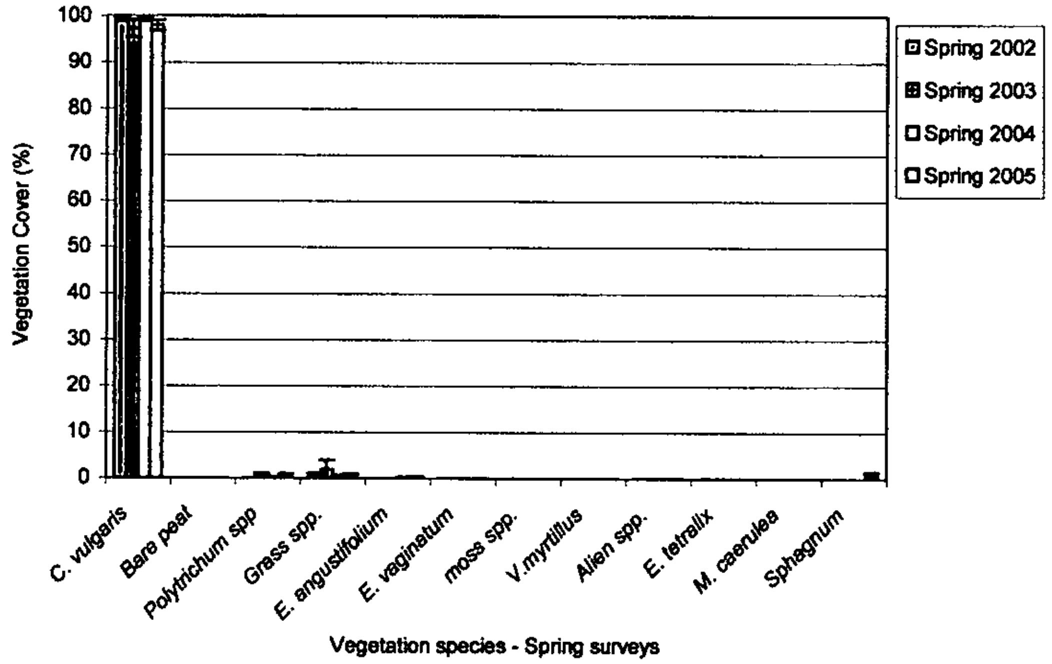


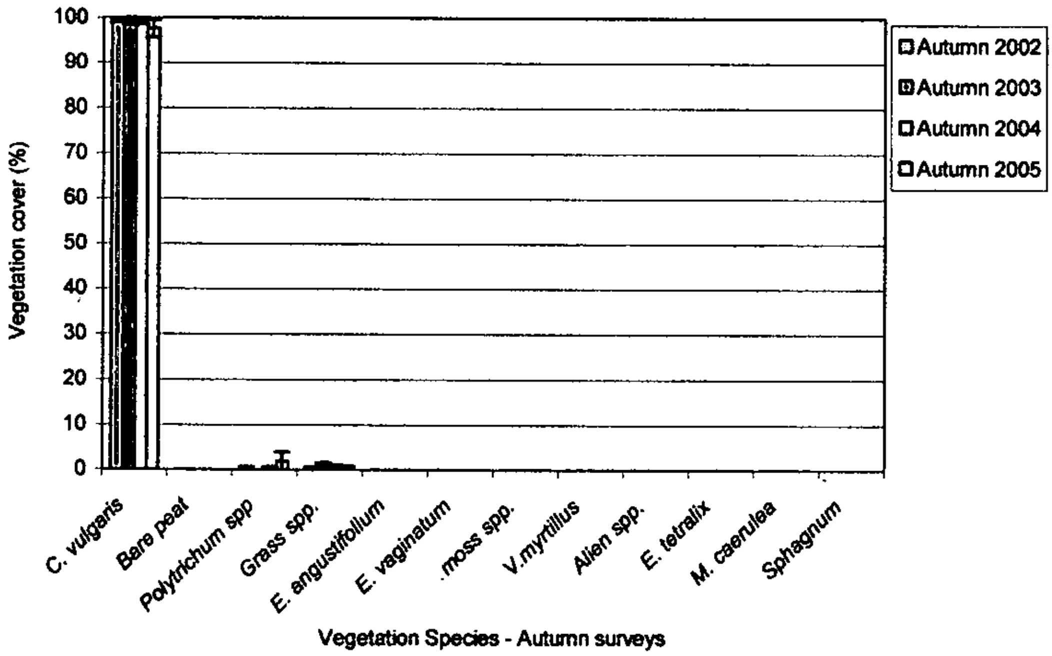
Quadrats 37-42 *Festuca spp*. sub-community.



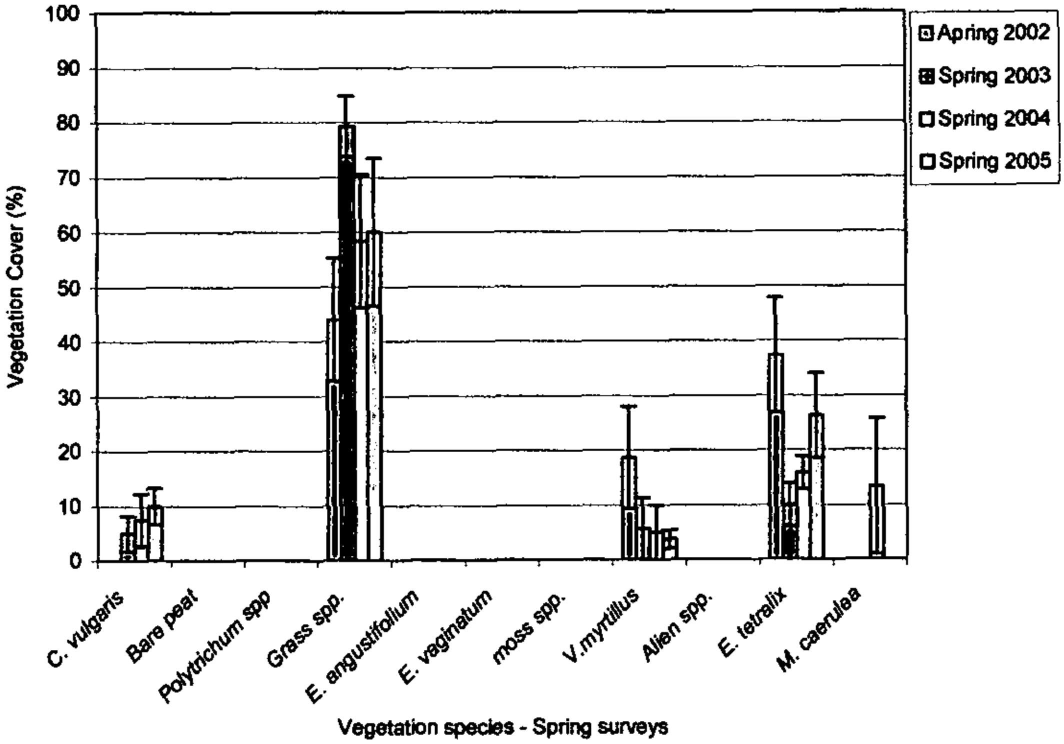


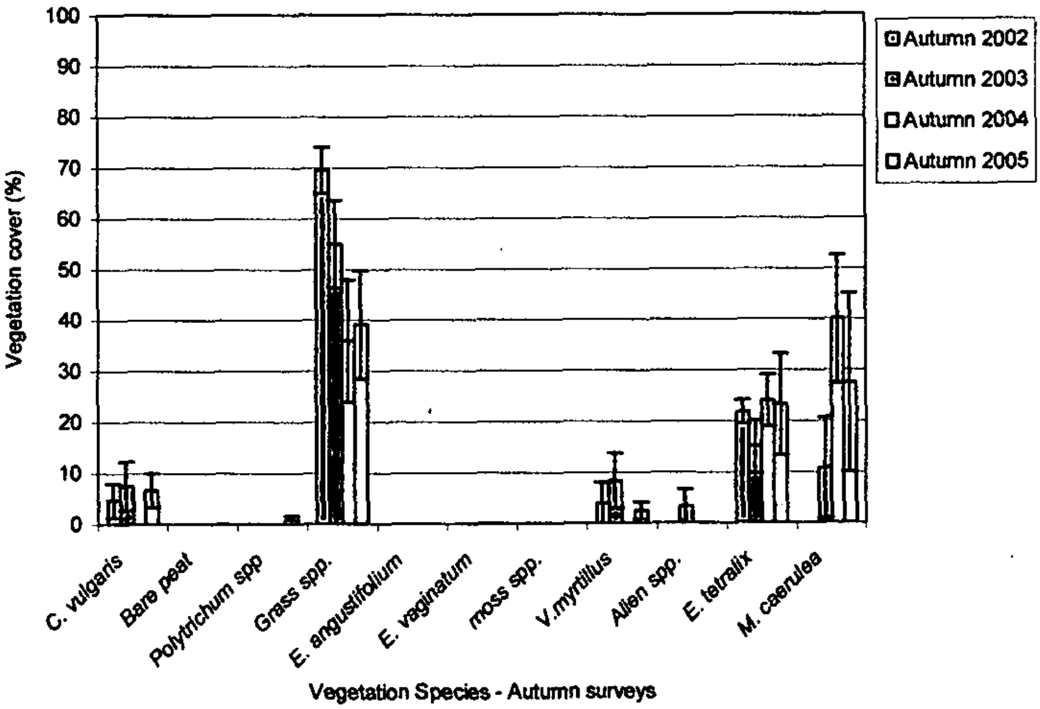
Quadrats 43-48 *C. vulgaris, Festuca spp.,Polytrichum spp* sub-community



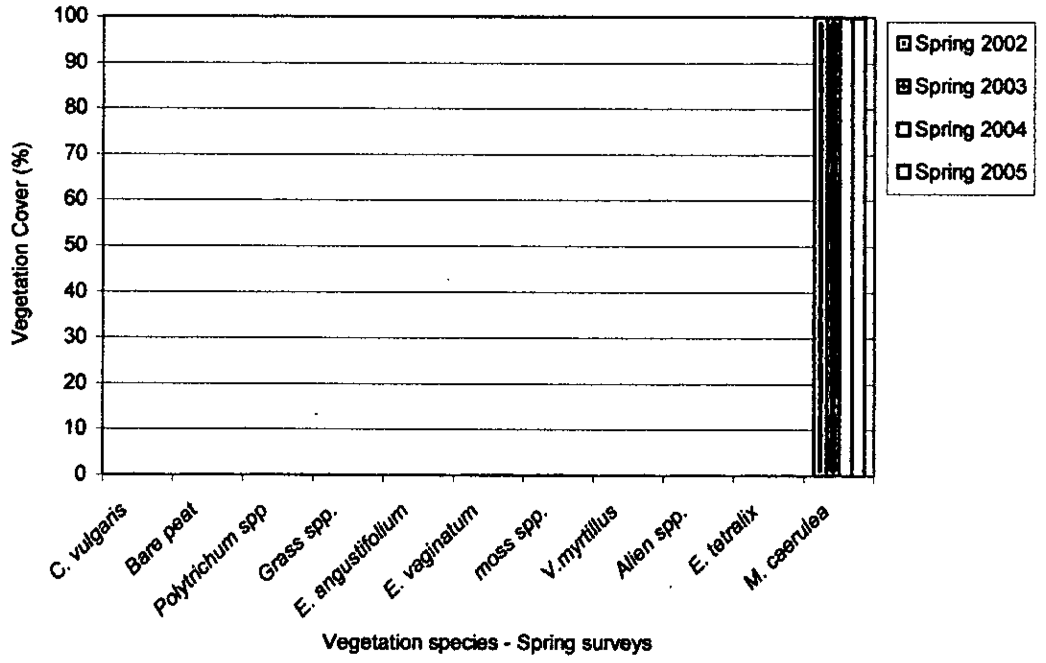


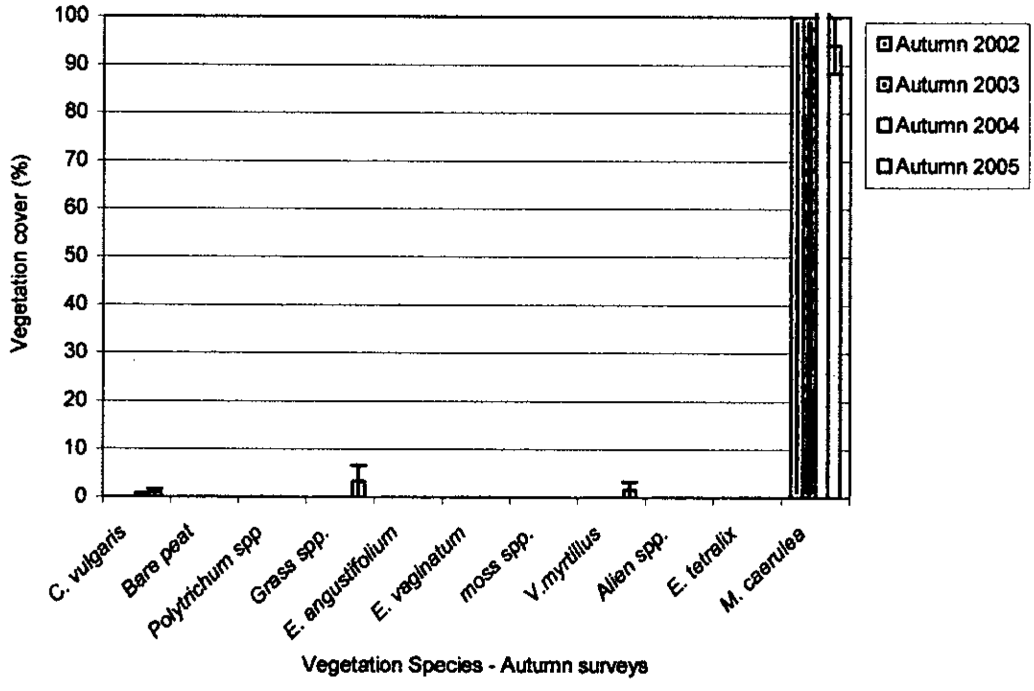
Quadrats 49-54 *C. vulgaris* sub-community





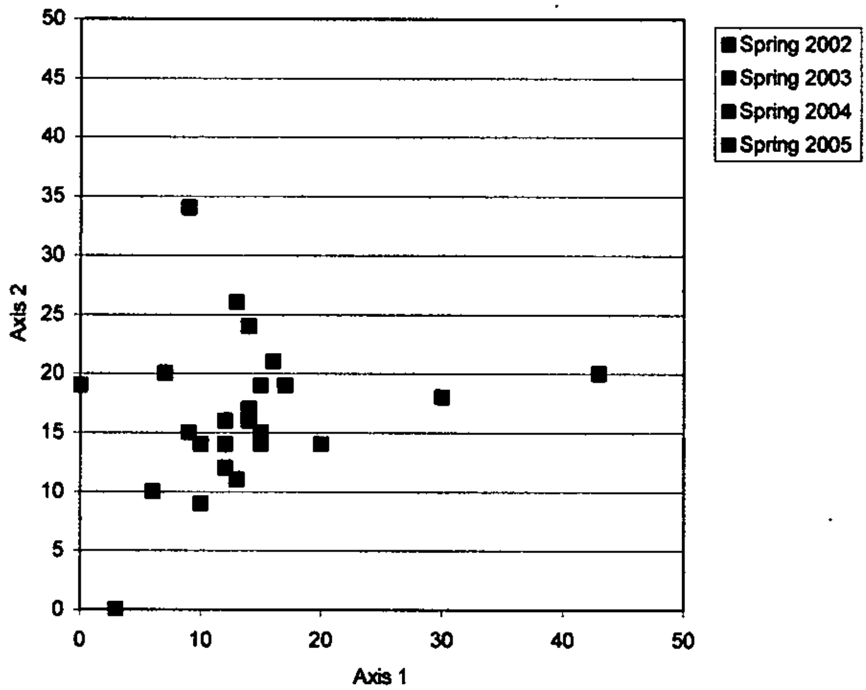
Quadrats 55-60 *E. tetralix* sub-community

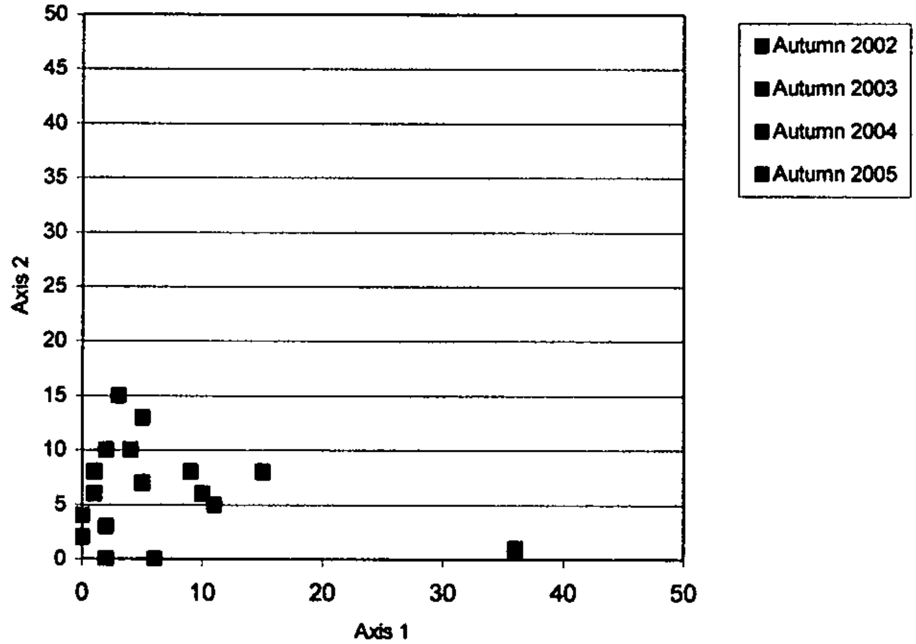




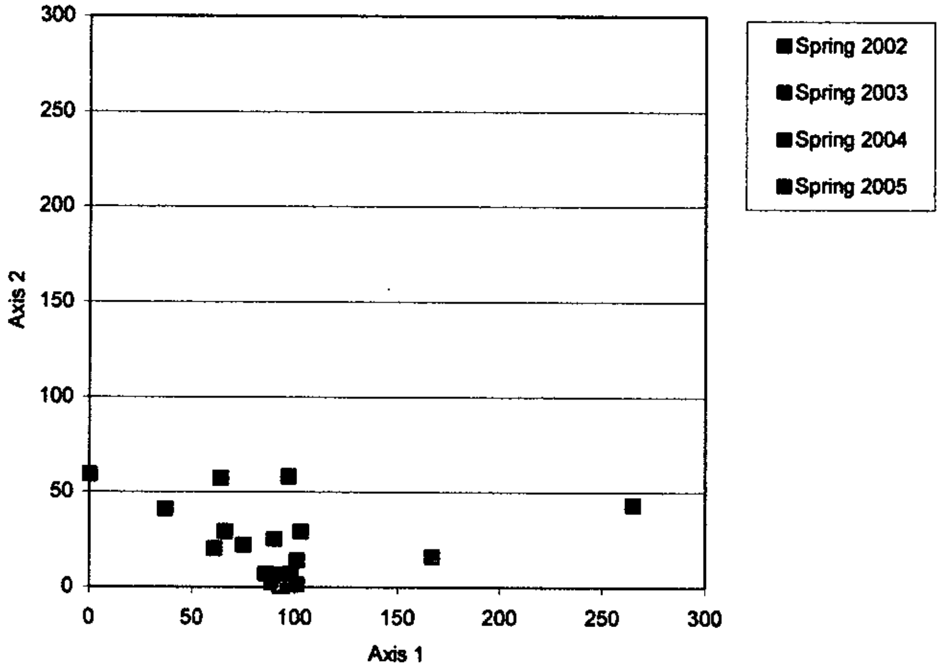
Quadrats 61-66 *M. caerulea.* sub-community

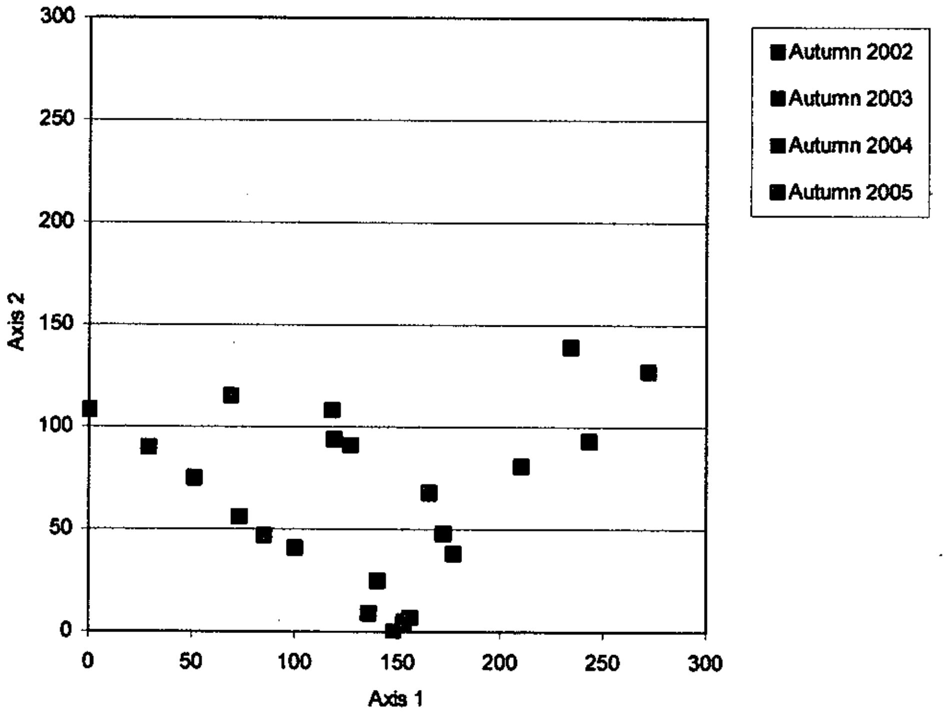
Appendix 5
Decorana results from the permanent quadrats for each sub-community as identified by TWINSPAN (Not all plots have the same scales).



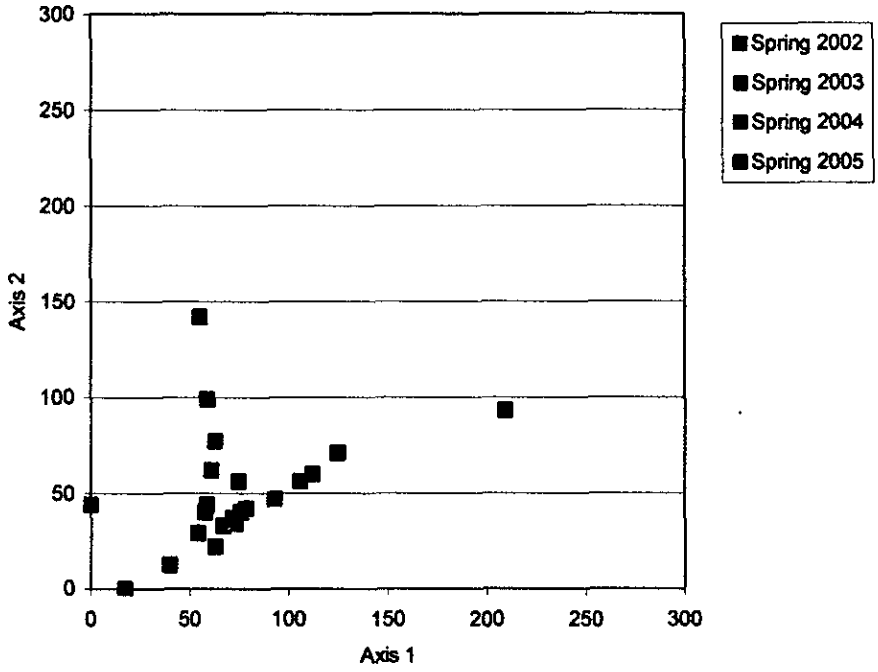


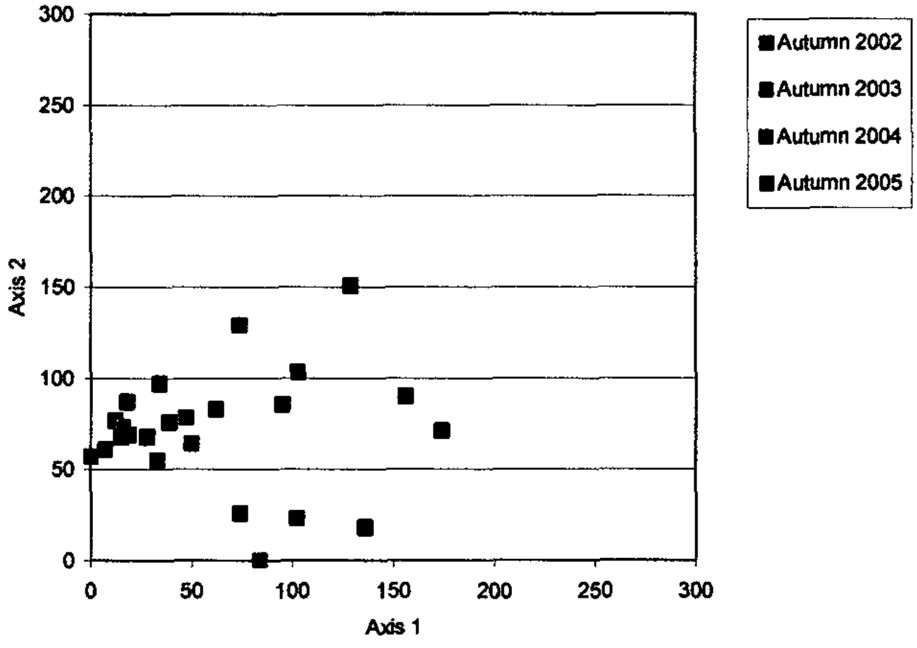
Quadrats 1-6 *Polytrichum spp*. Sub-community



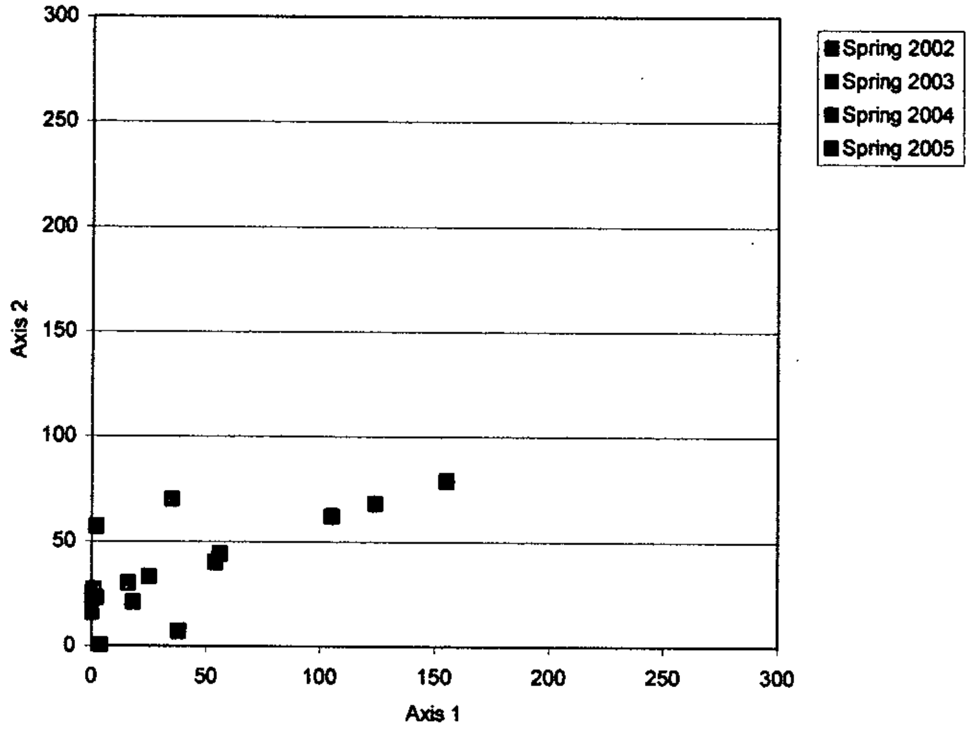


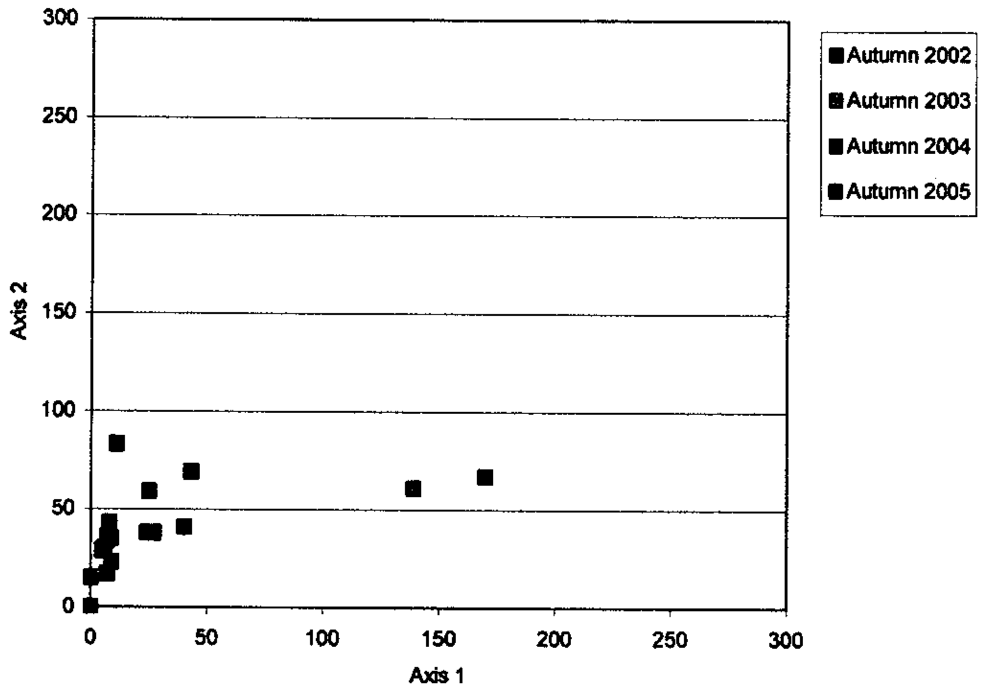
Quadrats 7-12. *E. angustifolium* sub-community



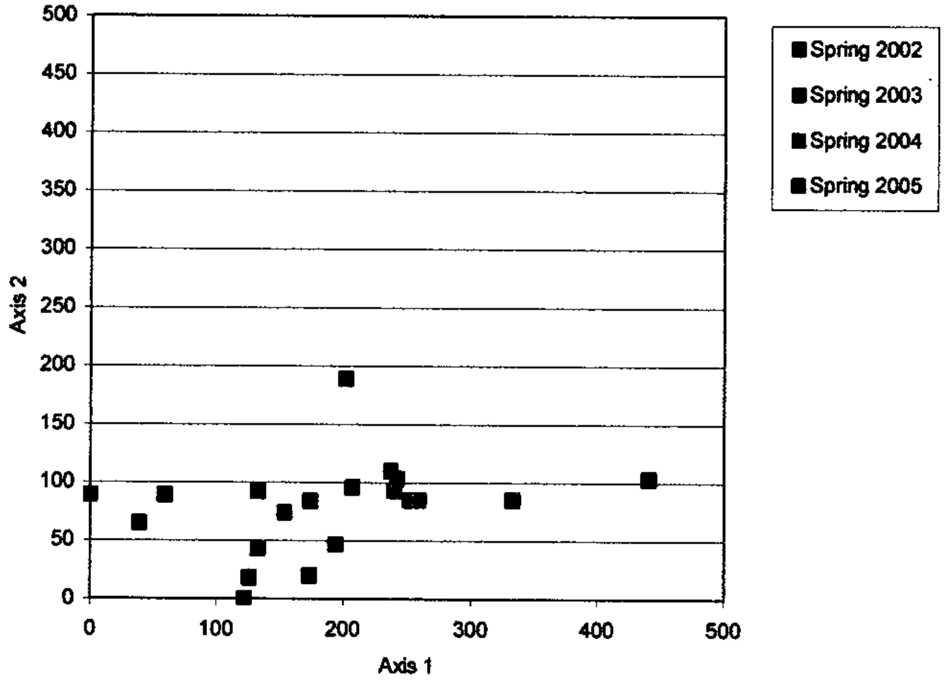


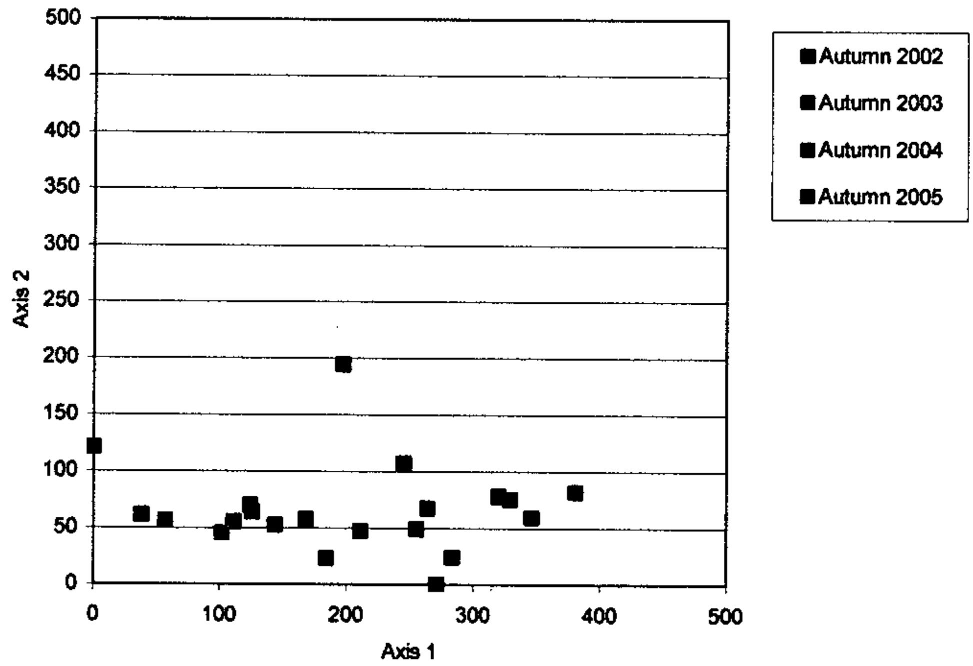
Quadrats 13-18 Bare peat, moss species sub-community.



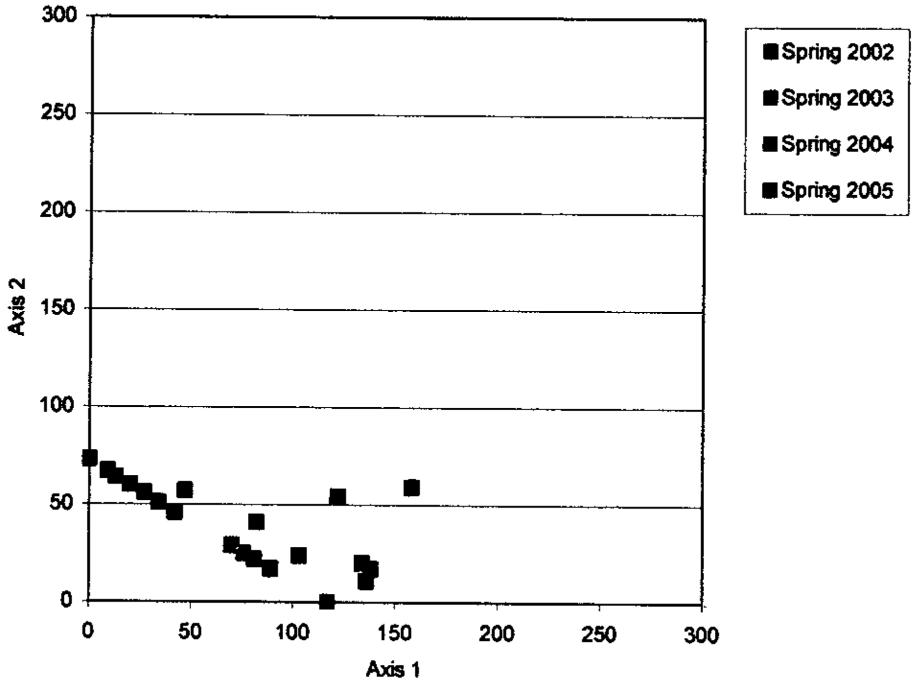


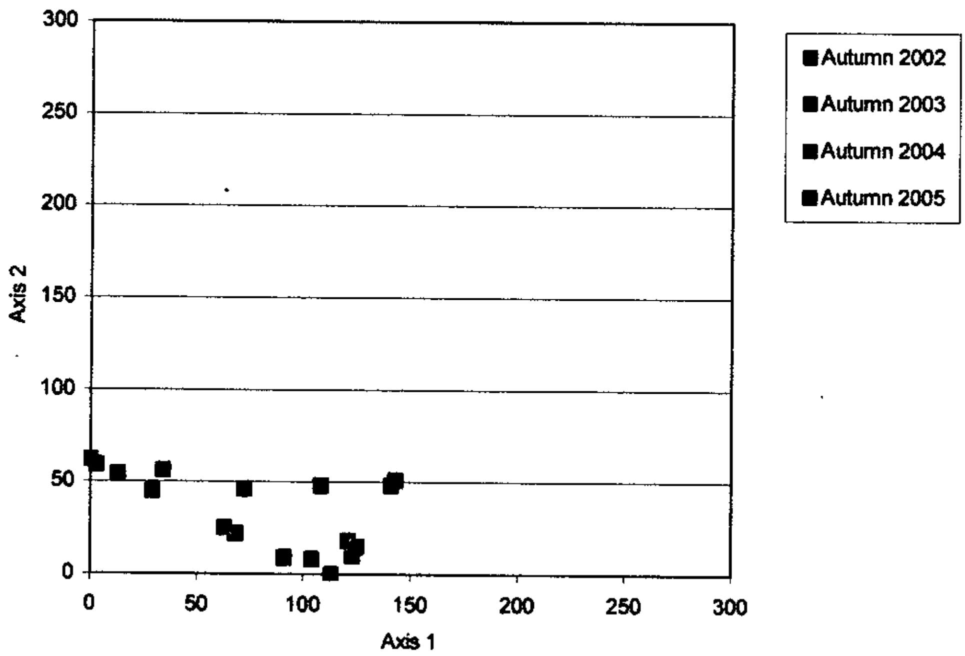
Quadrats 19-24 *E. vaginatum* sub-community.



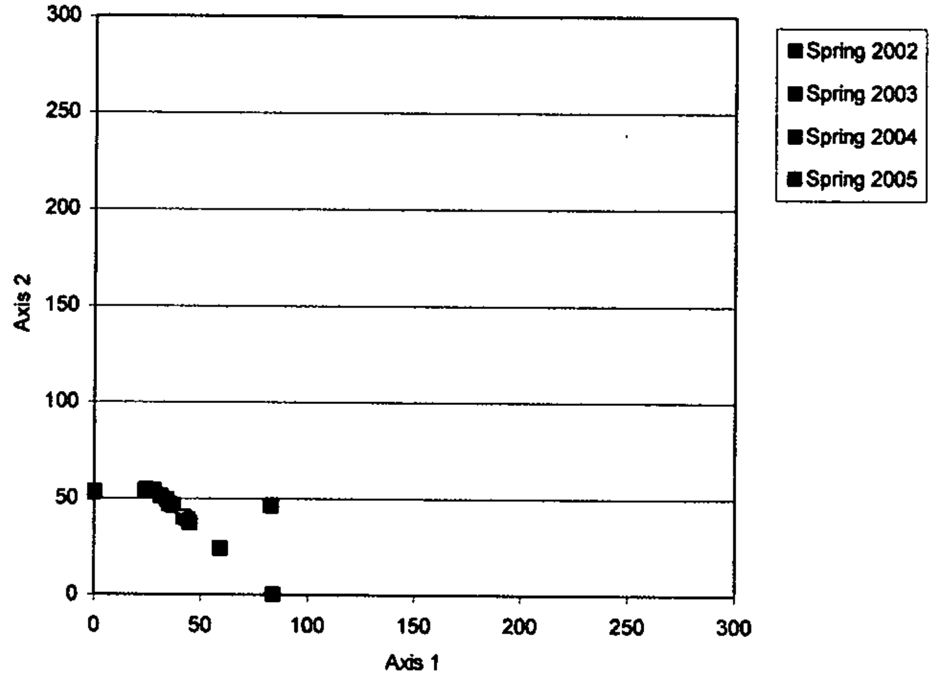


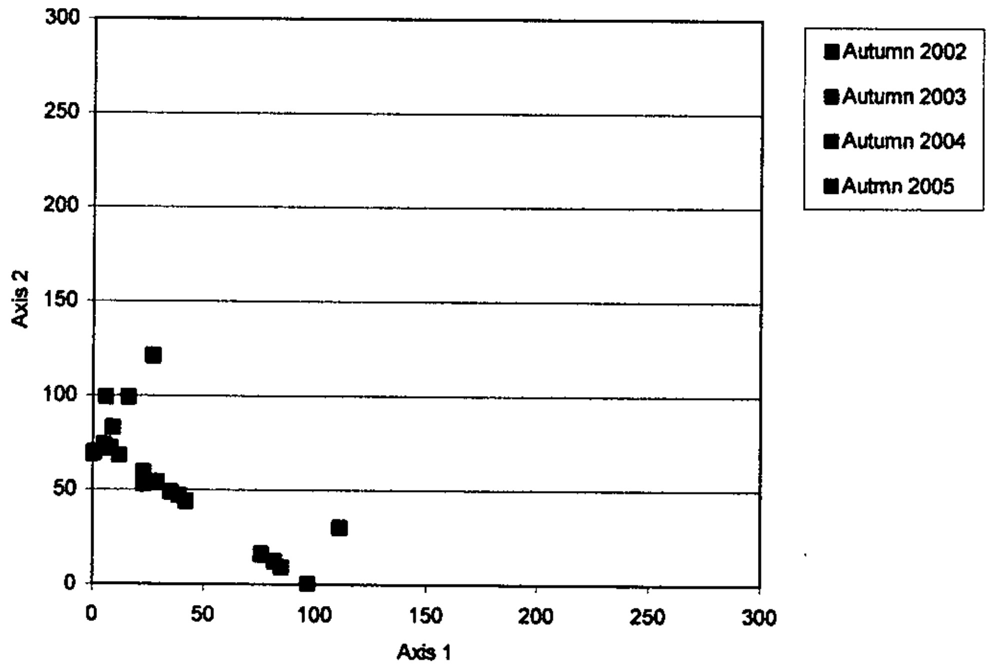
Quadrats 25-30 Burnt *C. vulgaris, V. myrtillus* sub-community.



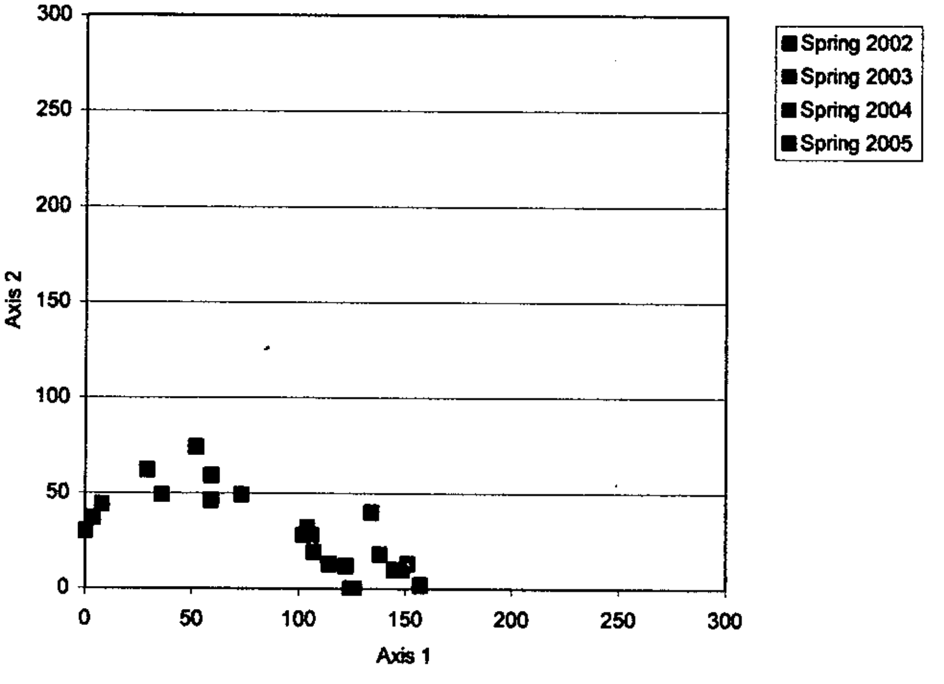


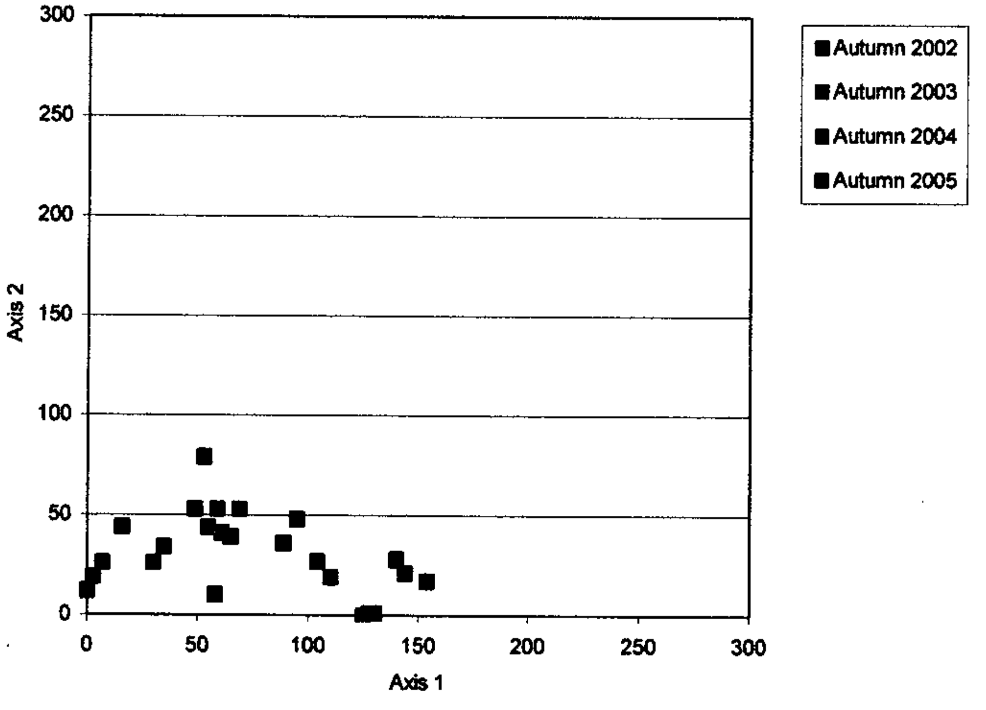
Quadrats 31-36 *Polytrichum sp., D. flexuosa* sub-community.



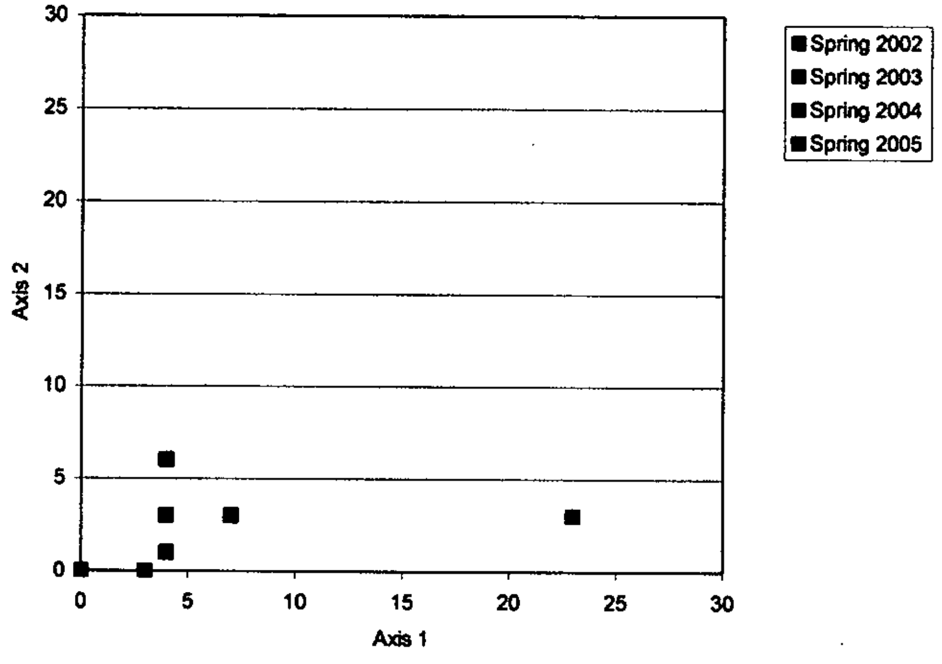


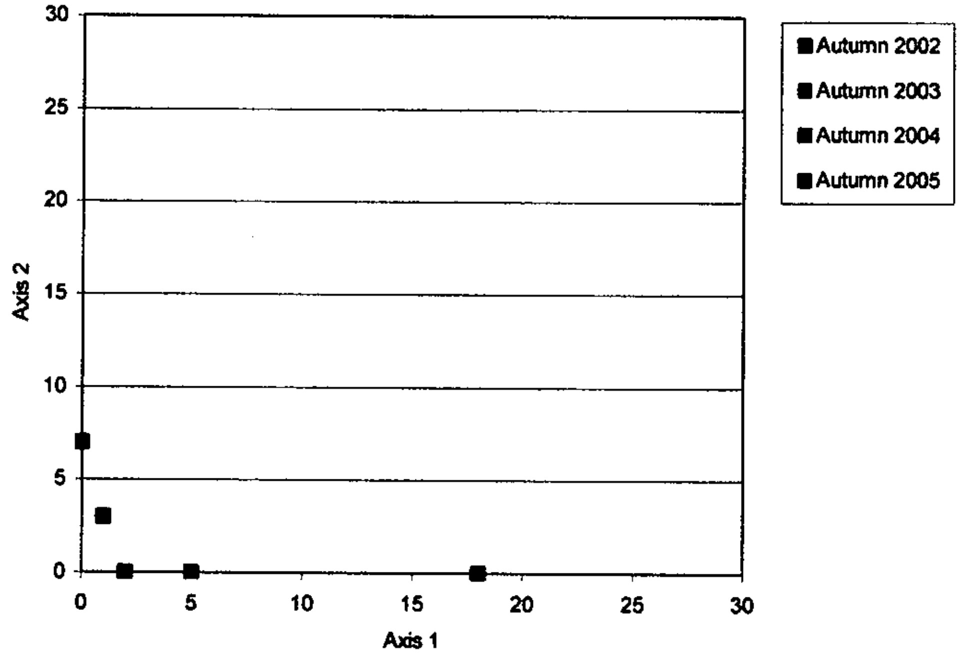
Quadrats 37-42 *Festuca spp* sub-community.



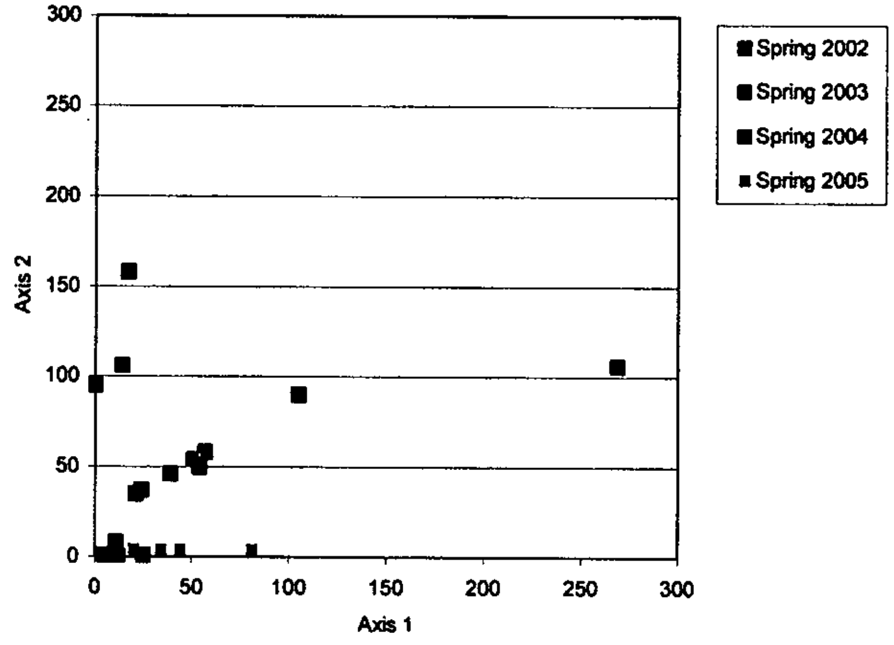


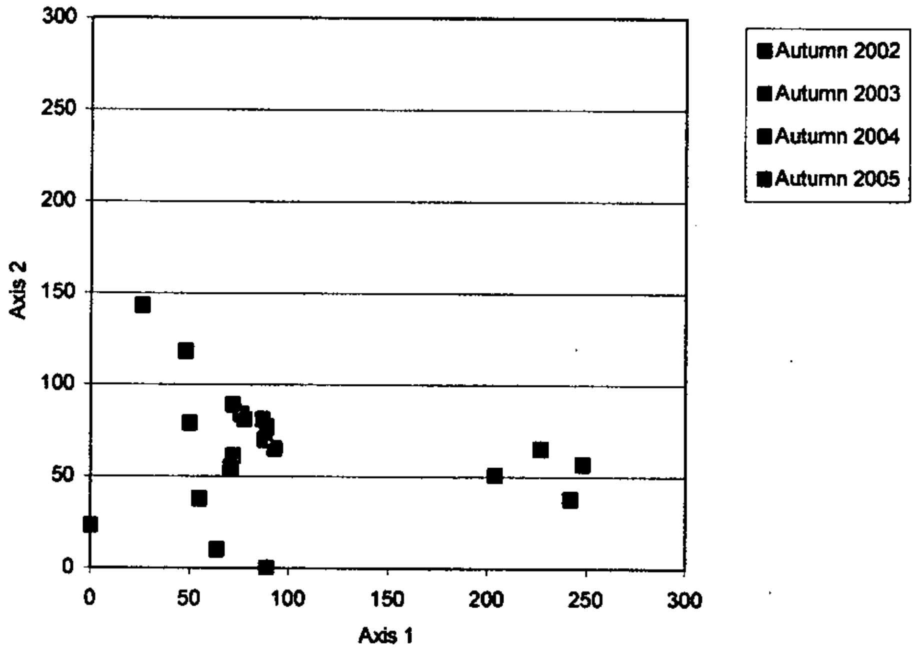
Quadrats 43-48 *C. vulgaris*, *Festuca spp.*,*Polytrichum spp.* sub-community.





Quadrats 49-54 *C. vulgaris* sub-community.

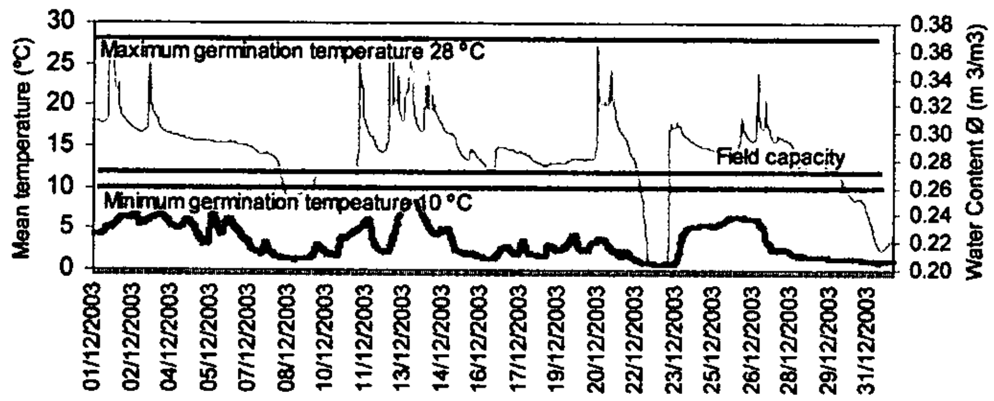




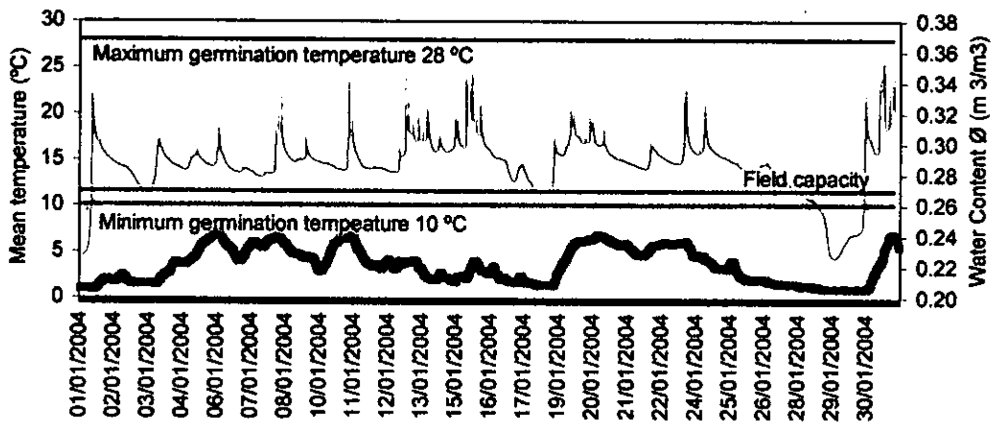
Quadrats 55-60 *E. tetralix* sub-community.

Appendix 6

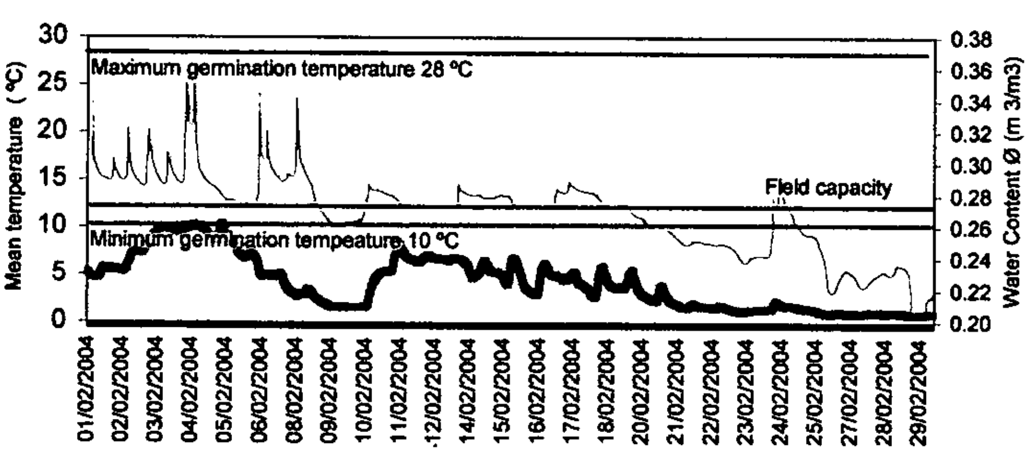
Datalogger results from the Stalybridge research site. Red line represents maximum and minimum germination temperature for *C. vulgaris*; data obtained from the appropriate literature. Blue line the field capacity of peat, calculated from peat samples.



December 2003

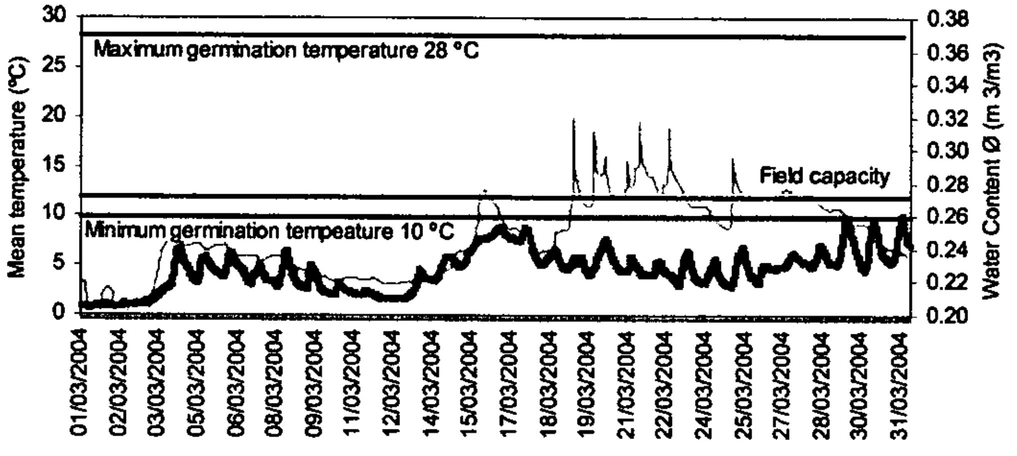


January 2004

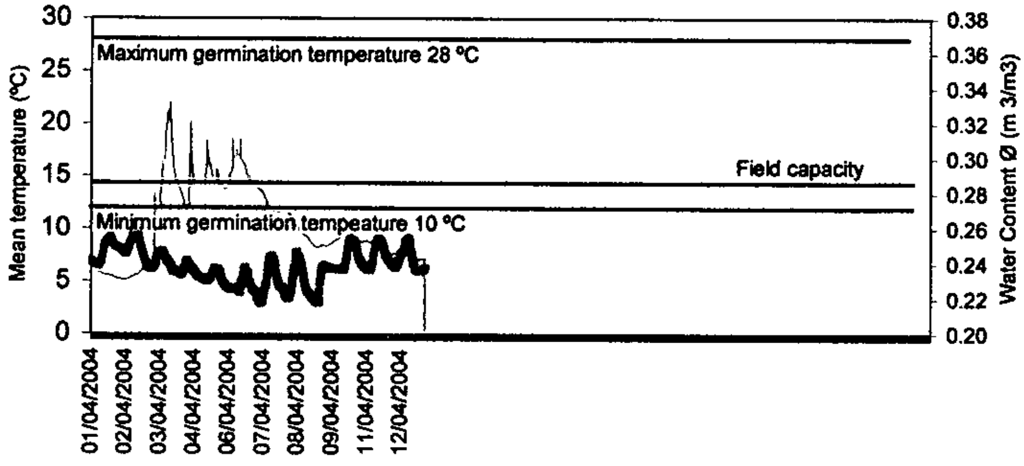


February 2004

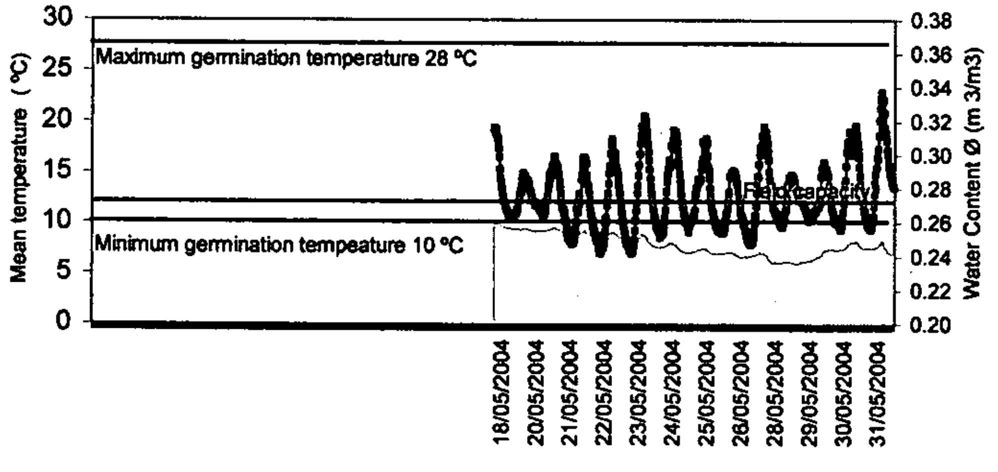
Temperature   Water content



March 2004

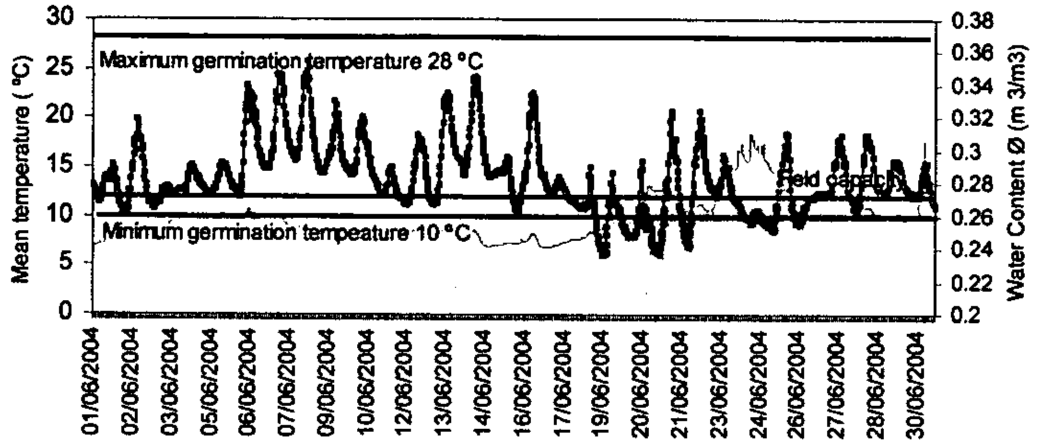


April 2004

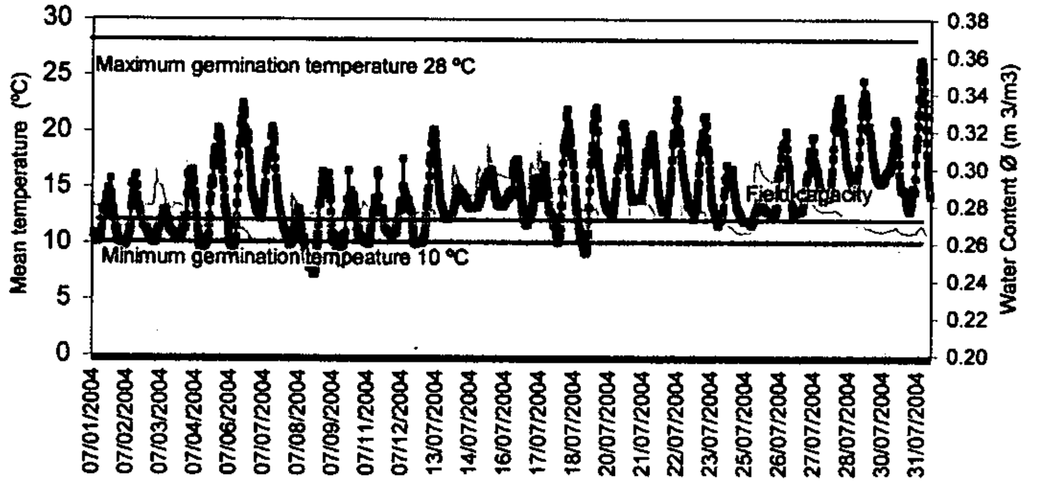


May 2004

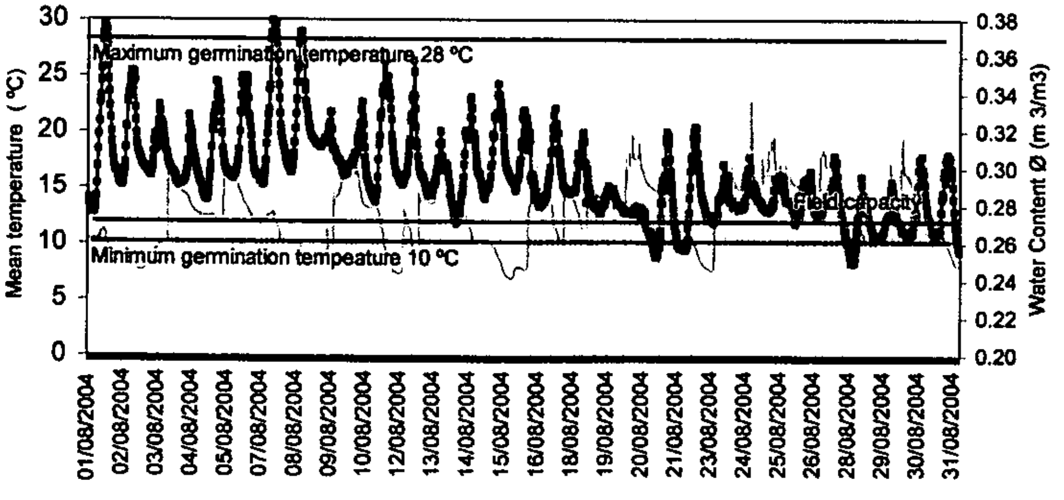
Temperature Water content



June 2004

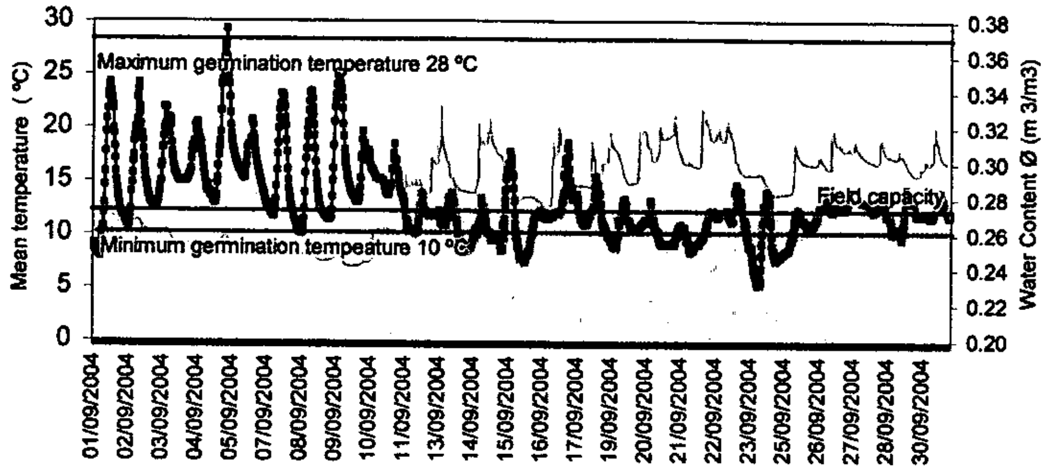


July 2004

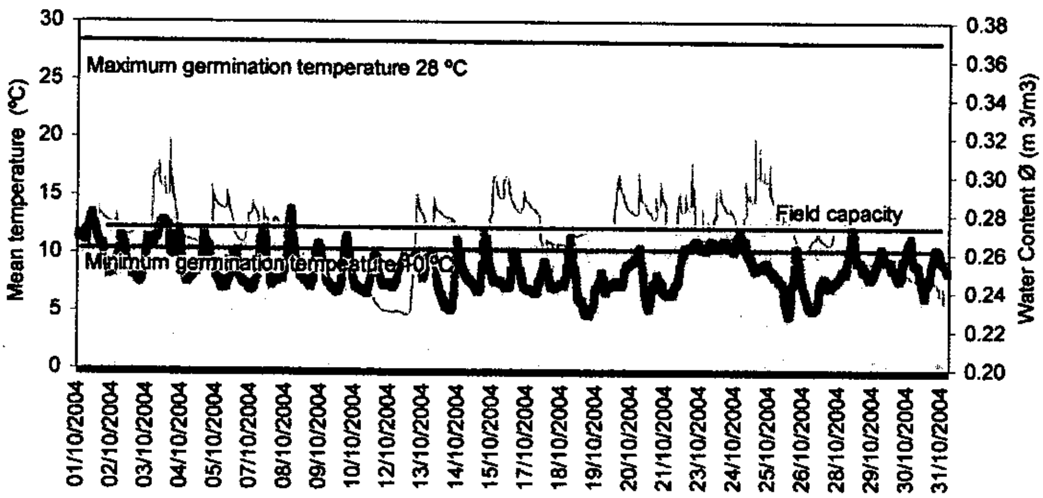


August 2004

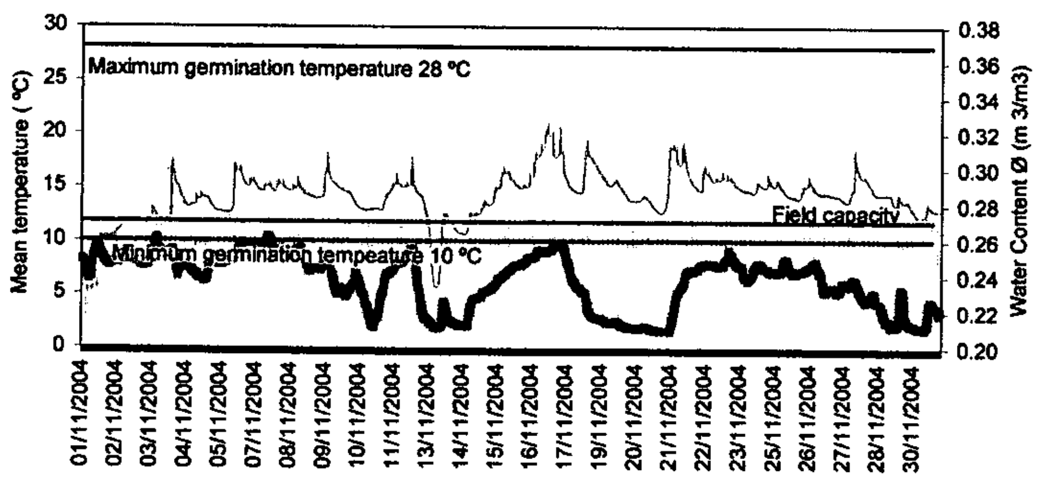
Temperature Water content



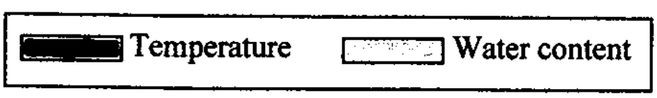
September 2004

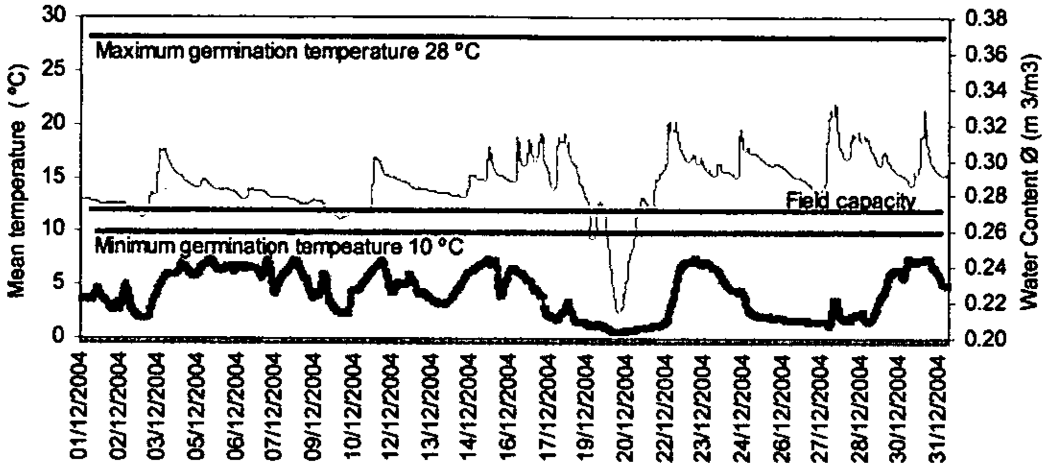


October 2004

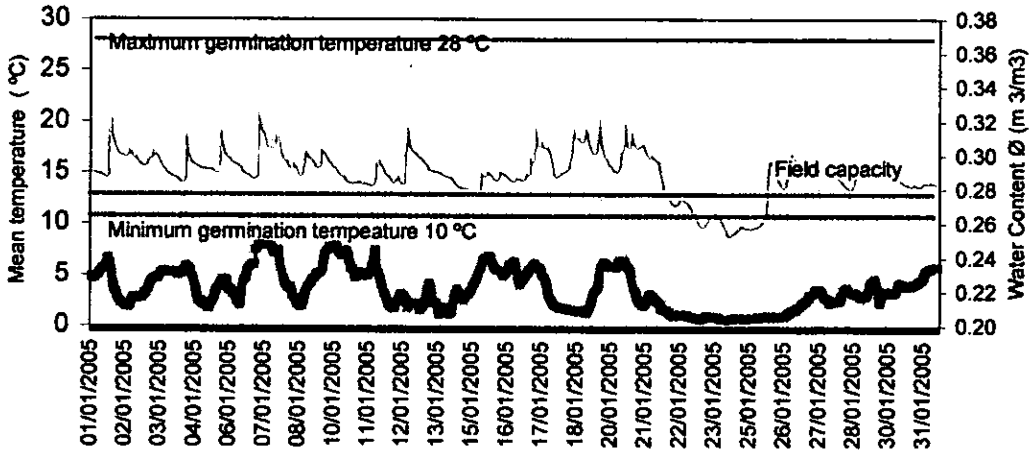


November 2004

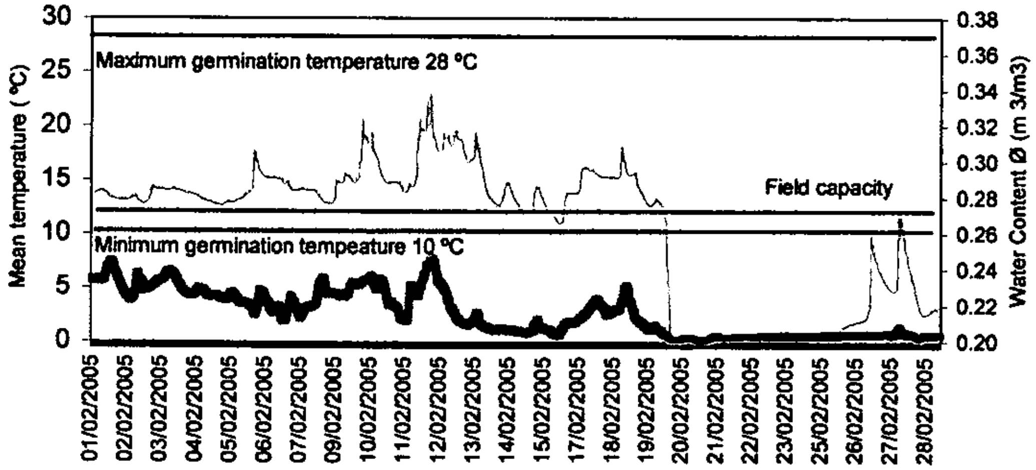




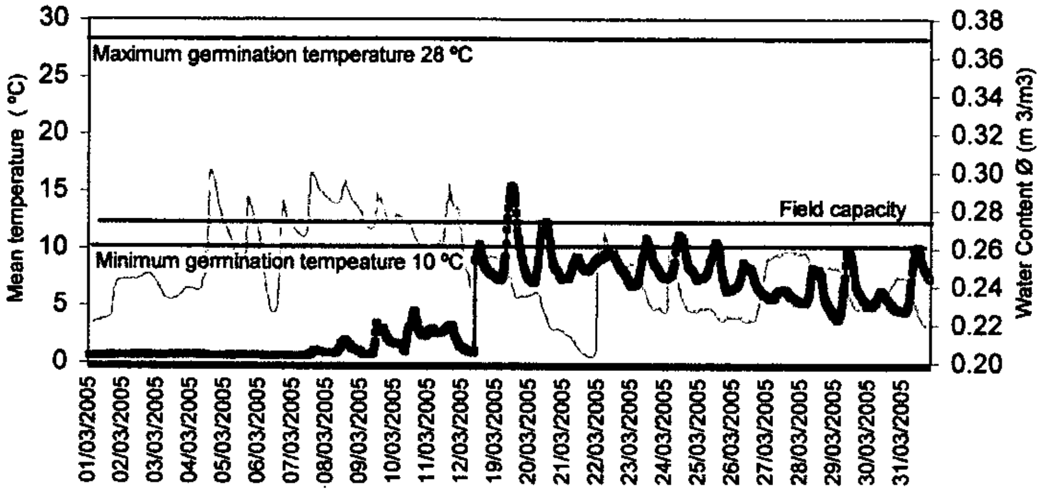
December 2004



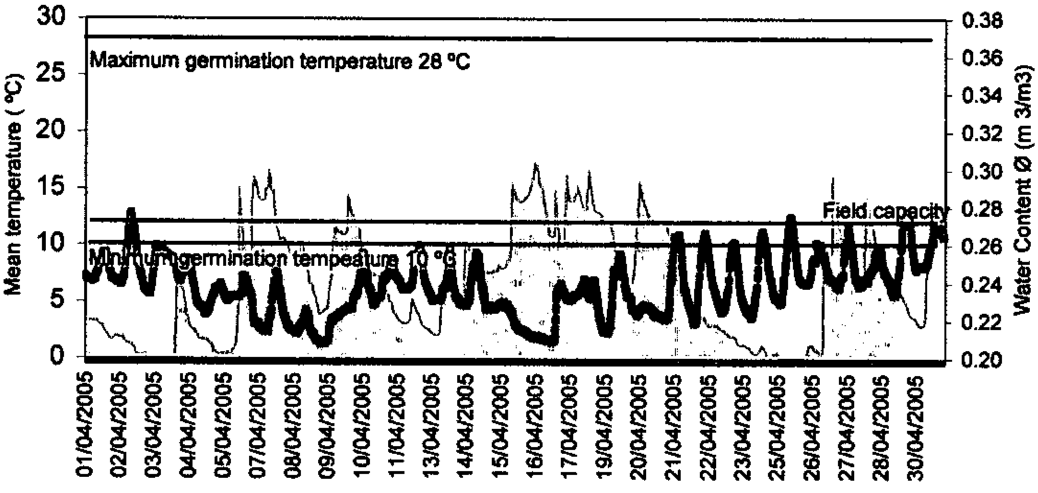
January 2005



February 2005



March 2005

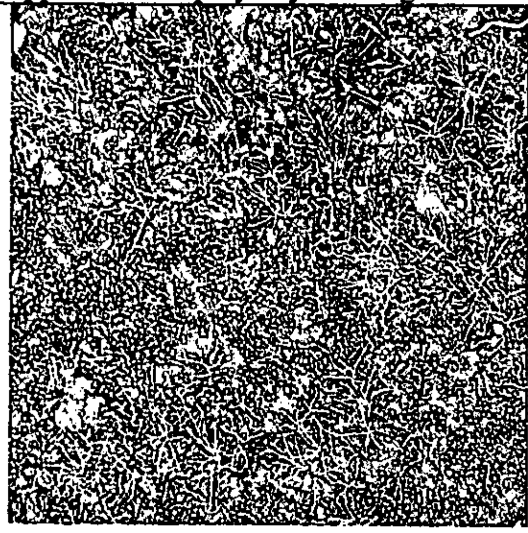
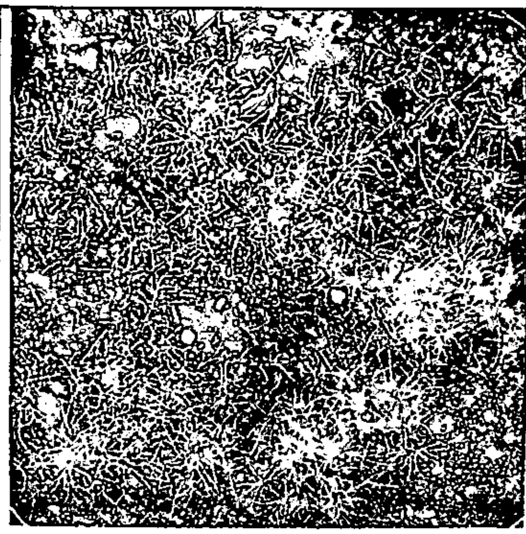
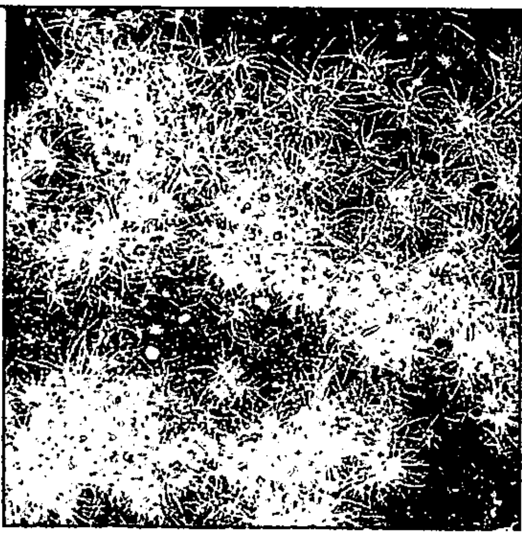
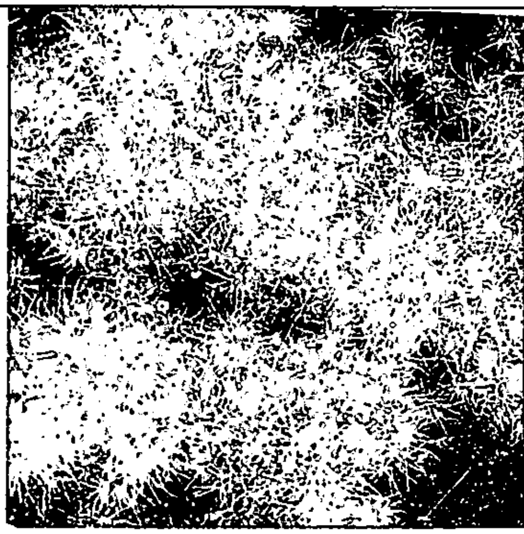
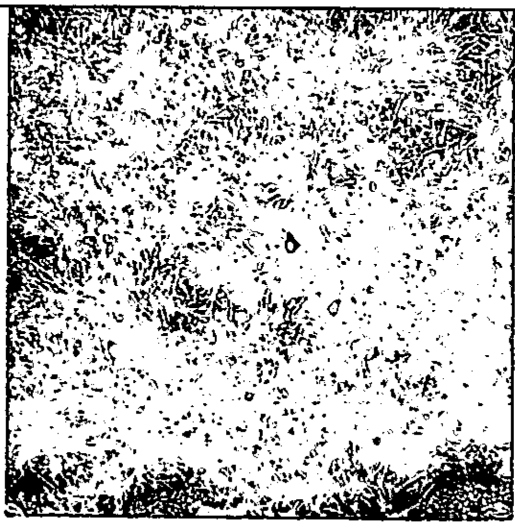


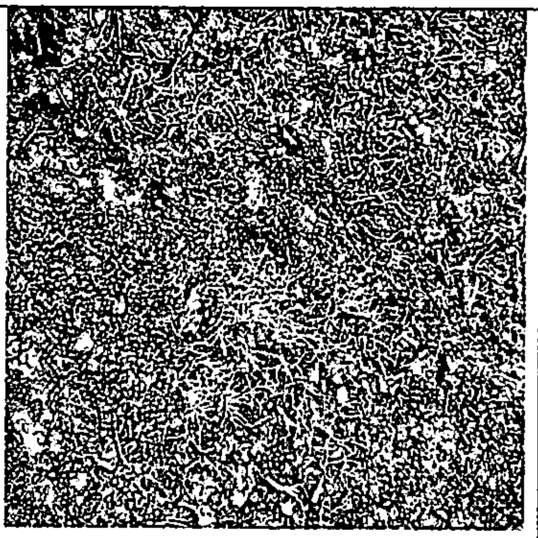
April 2005

Temperature Water content

Appendix 7 Grass cover in quadrats with or without polyacrylamide gel.

Digital images of grass cover on sample plots with an application of lime, fertiliser, and sown with mixed grass species (*A. castellana, F. rubra*). Samples 1 –3 also had an application of polyacrylamide gel.

 1	 2
 3	 4
 5	Sample 1 Sampling dates 1 – 12th August 2004 2 – 2nd September 2004 3 – 28th September 2004 4 – 18th March 2005 5 – 22nd September 2005 With application of polyacrylamide gel



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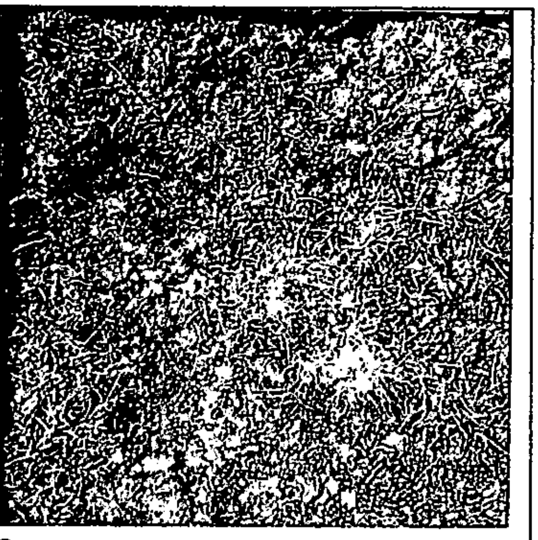

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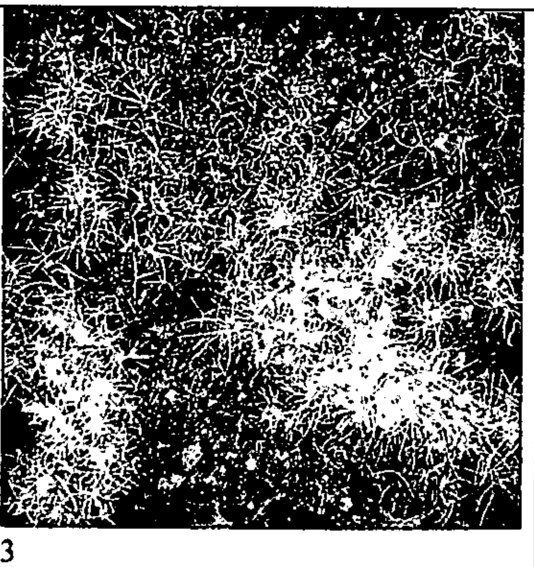

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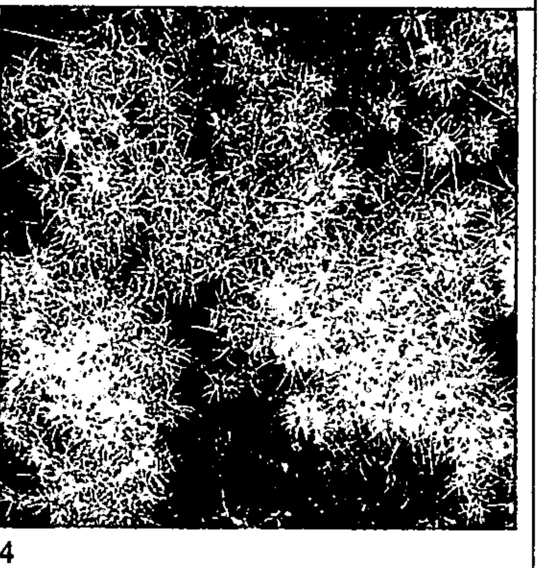

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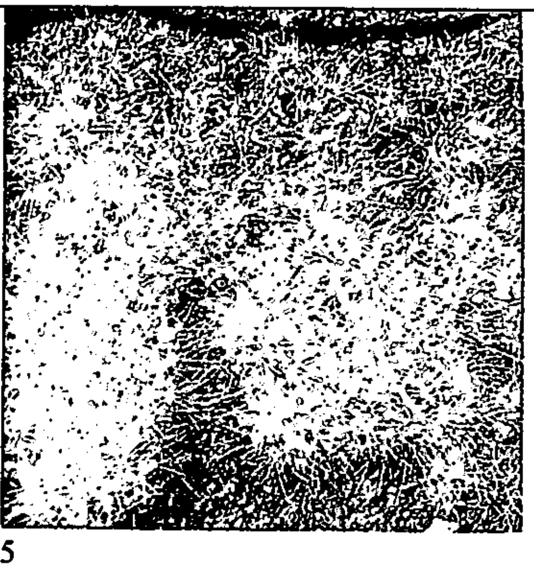
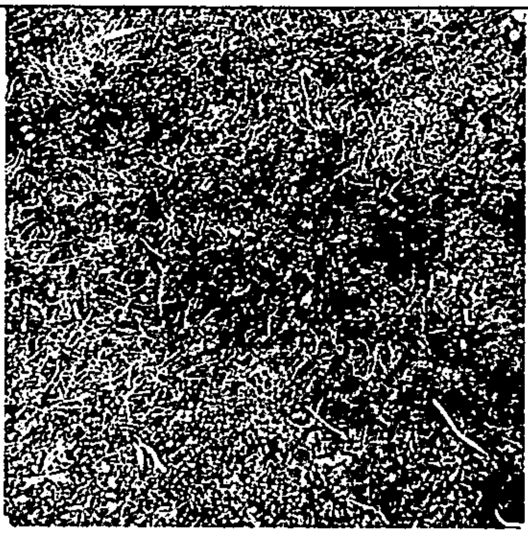


5

Sample 2

Sampling dates
1 – 12th August 2004
2 – 2nd September 2004
3 – 28th September 2004
4 – 18th March 2005
5 – 22nd September 2005

With application of polyacrylamide gel



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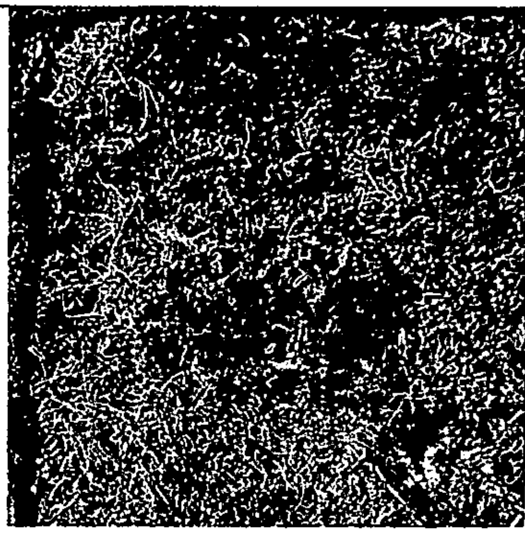

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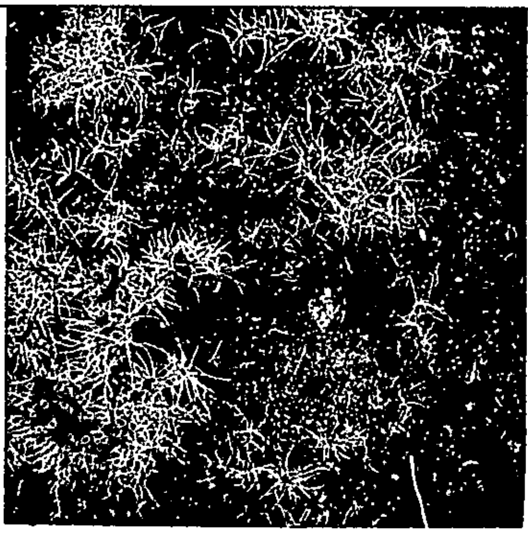

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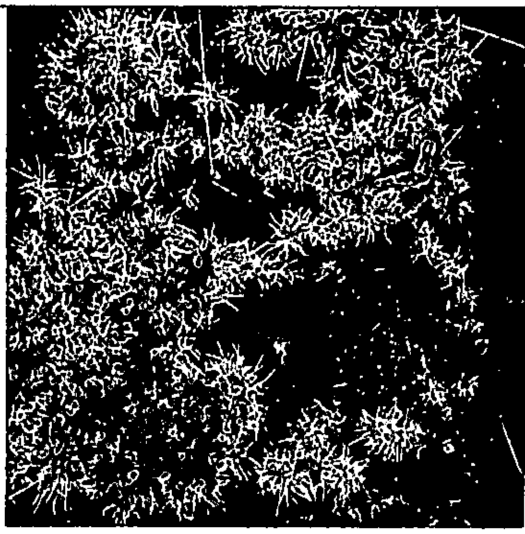

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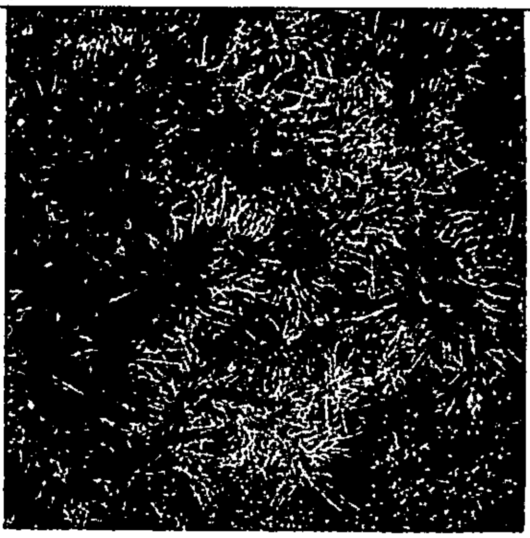
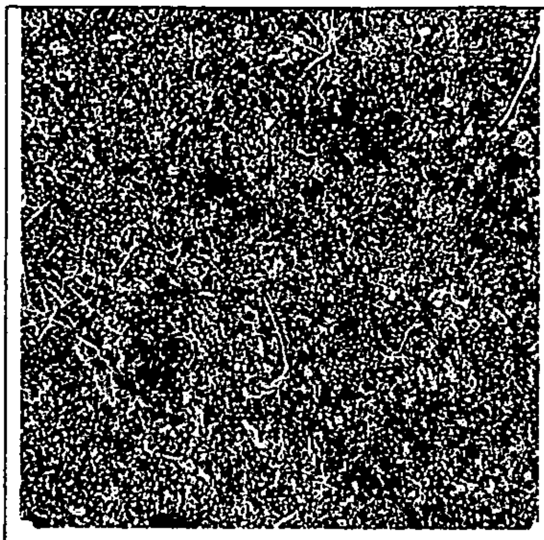


5

Sample 3

Sampling dates
1 – 12th August 2004
2 – 2nd September 2004
3 – 28th September 2004
4 – 18th March 2005
5 – 22nd September 2005

With application of polyacrylamide gel



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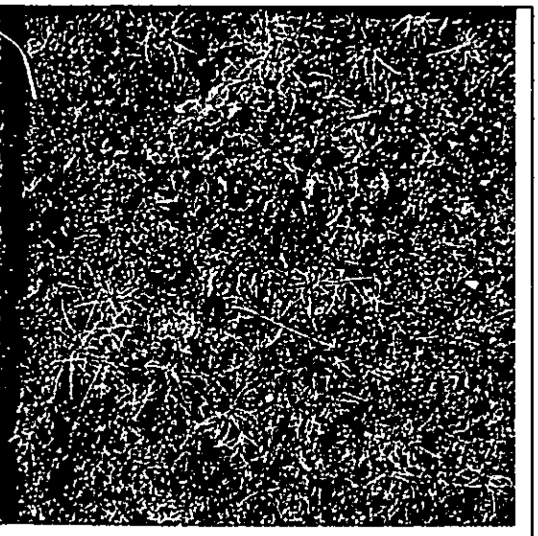

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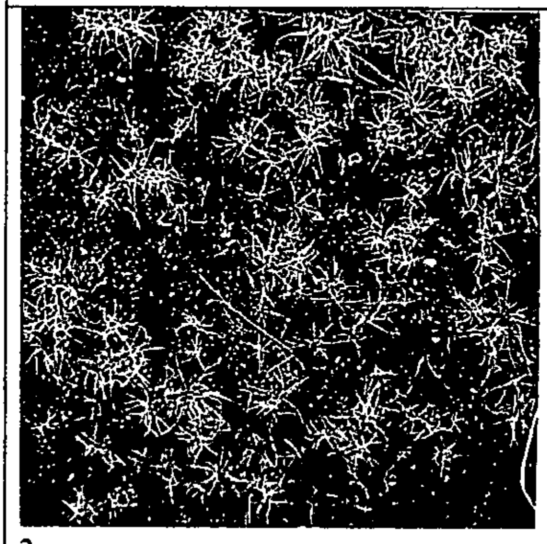

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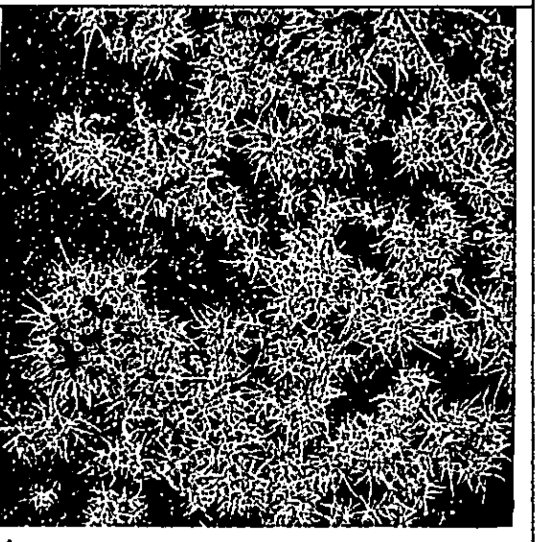

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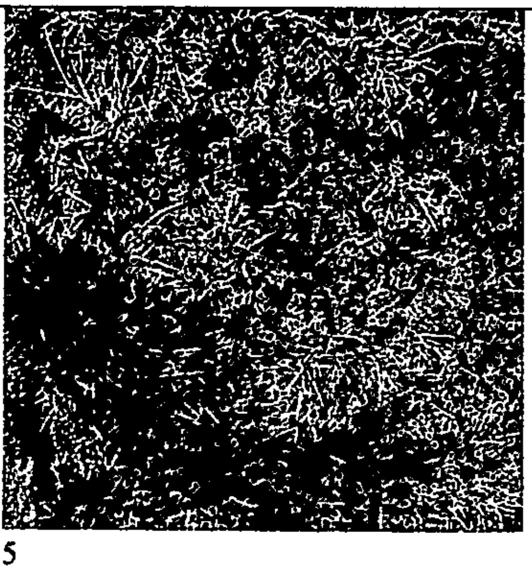

5

Sample 4

Sampling dates
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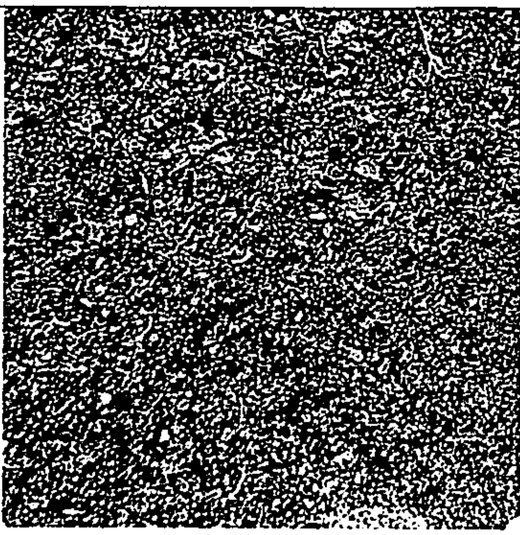
2 – 2nd September 2004
3 – 28th September 2004
4 – 18th March 2005
5 – 22nd September 2005

No polyacrylamide gel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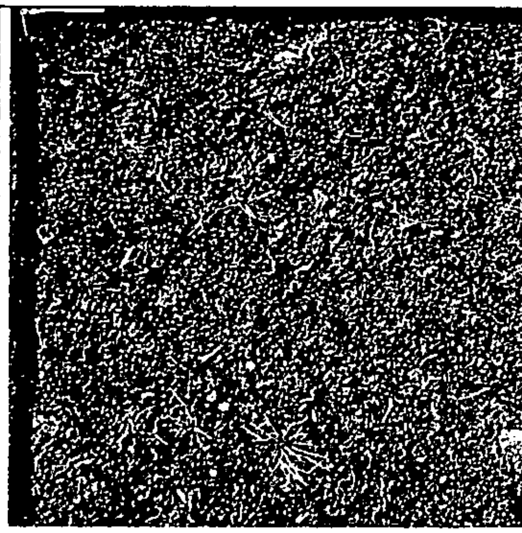
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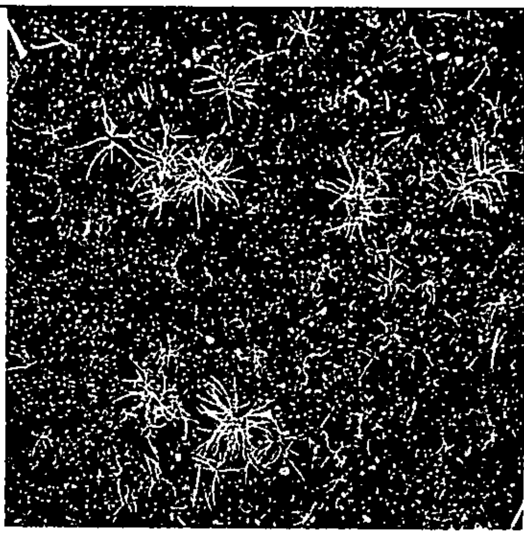
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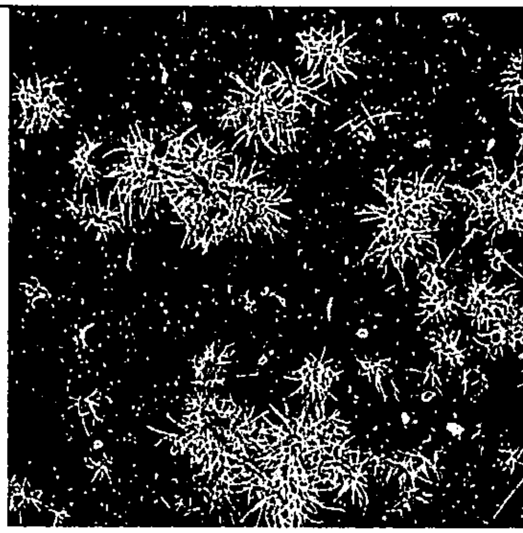
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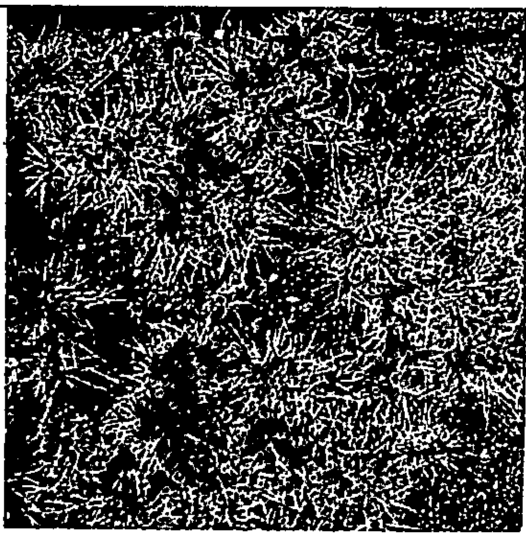
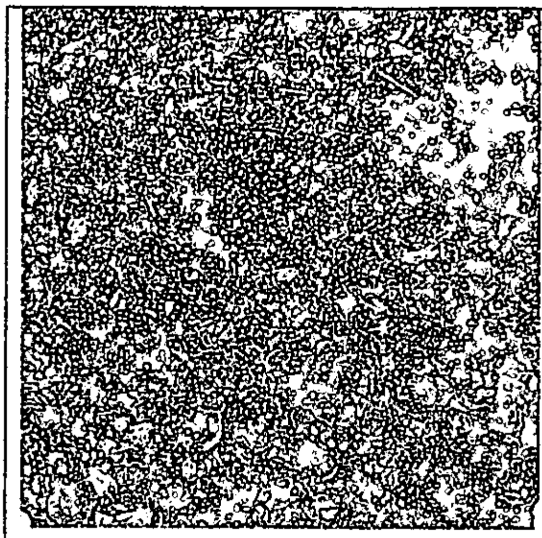

5

Sample 5

Sampling dates
1 – 12th August 2004
2 – 2nd September 2004
3 – 28th September 2004
4 – 18th March 2005
5 – 22nd September 2005

No polyacrylamide gel

6



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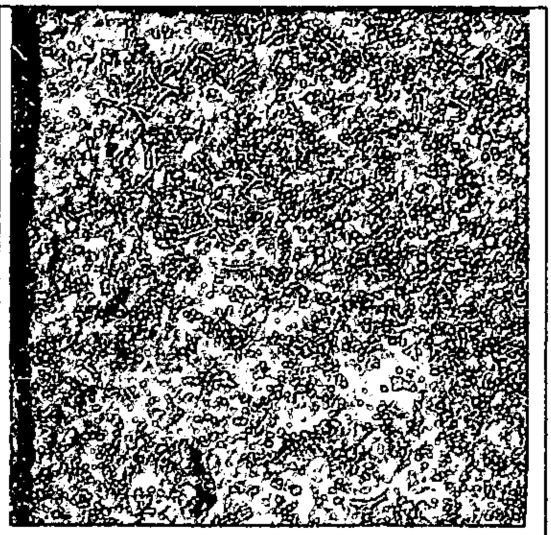

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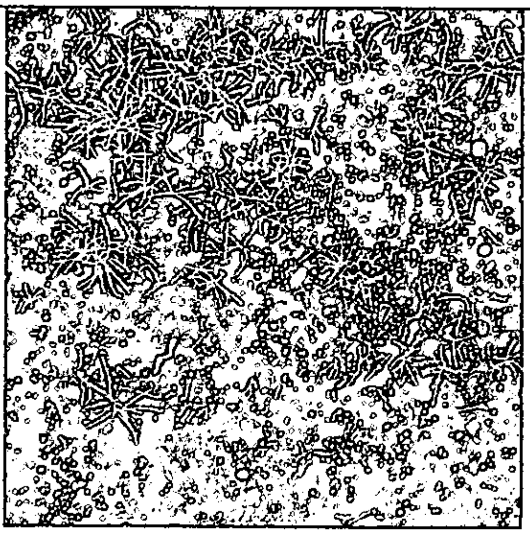

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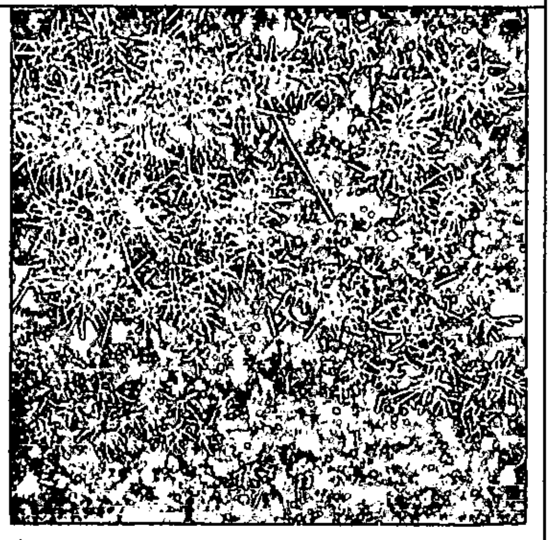

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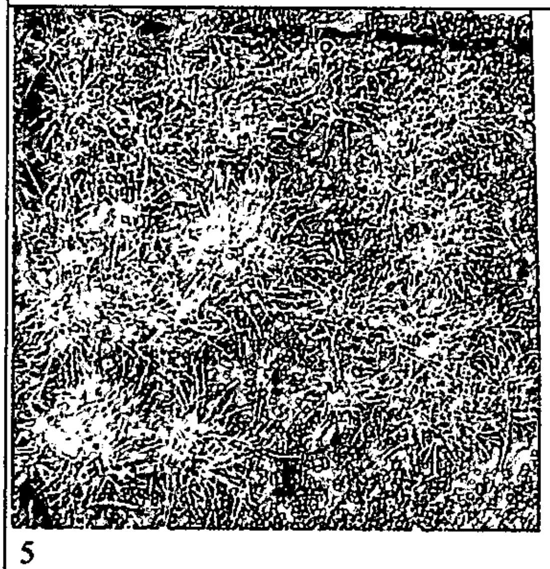

5

Sample 6

Sampling dates
1 – 12th August 2004
2 – 2nd September 2004
3 – 28th September 2004
4 – 18th March 2005
5 – 22nd September 2005

No polyacrylamide gel