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The Flora and Conservation Status of Petrifying Springs in Ireland

Thesis submitted for the Degree of

Doctor of Philosophy

by

Melinda D. Lyons

May 2015

Based on research carried out under the supervision of

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Summary

Petrifying springs are lime-rich water sources which deposit tufa, a soft, porous rock. They constitute a highly specialised habitat with a distinctive floristic composition, typically dominated by bryophytes and often containing rare species. Their small extent and vulnerability is recognised by their designation as the priority habitat 'Petrifying Springs with Tufa Formation (*Cratoneurion*)' under the European Union Habitats Directive (92/43/EEC).

This study is the first comprehensive field-based survey of petrifying springs in Ireland: 186 relevés ($4m^2$) were recorded island-wide from 73 sites, located in 18 counties, between April 2011 and September 2014. Relevés were assigned to groups by Fuzzy Cluster analysis, based on their floristic composition, and eight plant communities of Irish petrifying springs were described for the first time. Group 1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades form on steep slopes, often with massive consolidated tufa deposits; their vegetation is dominated by bryophytes and they have affinities with *Adiantion* communities of damp cliffs. Group 2 *Palustriella commutata-Geranium robertianum* Springheads typically form on wooded hillsides, often giving rise downslope to flush vegetation constituting the Group 3 community, *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes; both are strongly tufa-forming, shaded communities, related to the *Equiseto telmatejae-Fraxinetum* Oberd. ex Seib. 1987. Group 4 *Palustriella commutata-Agrostis stolonifera* Springheads are intermediate in many respects between Groups 1 to 3 and Groups 5 to 8; they are unshaded, occurring on gentle to moderate slopes and dominated by a combination of bryophytes and graminoids. Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs contain a more diverse range of species than Groups 1 to 4; they are transitional between *Cratoneurion* petrifying spring communities and *Caricion davallianae* small-sedge fen communities. They occur on level ground and range from being weakly tufaceous to forming conspicuous deposits of consolidated paludal tufa. Group 7 *Palustriella falcata-Carex panicea* Springs reach their fullest expression in the Burren; they also occur, for example, on the lower slopes of the Benbulbin Range. They are characterised by mosaics containing a high proportion of level or gently sloping unvegetated surfaces; in the Burren, this takes the form of thin stream crust tufa overlying limestone pavement. Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs constitute a highly specialised community on steep cliffs of the Benbulbin Range. They contain a suite of rare bryophytes: *Seligeria oelandica, S. patula, Hymenostylium recurvirostrum* var. *insigne* and *Orthothecium rufescens*. They are weakly-tufa forming, typically producing a thin film of stream crust tufa over vertical rock exposures.

All of the communities described are ecologically distinctive and worthy of conservation. Group 8 *Saxifraga aizoides-Seligeria oelandica* springs of the Benbulbin Range are of highest conservation value; they are important at an international level, due to the rare bryophytes they contain.

Analysis of the chemical composition of water from 91 separate Irish petrifying springs (115 water samples in total) found that pH ranged from 7.00 to 8.47. Calcium and alkalinity levels were high throughout (mean calcium 87.0 mg/l and mean bicarbonate 293.7 mg/l). Concentrations of nitrates and phosphates were generally low; 83.5% of samples contained less than 10 mg/l nitrate and 57.4% contained less than 15 µg/l phosphate. Six samples (5.2%) had nitrate levels in excess of 30 mg/l and nine samples (7.8%) had phosphate concentrations in excess of 30 µg/l (one sample fell into both of these categories). These concentrations are cause for concern; species diversity was significantly lower where spring waters contained elevated nitrate or phosphate levels. Group 8 *Saxifraga aizoides-Seligeria oelandica* springs had the highest pH values and the lowest mean concentrations for all solutes; any change to the chemical composition of the spring waters irrigating this community is likely to be deleterious to its conservation status. Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Springs and Flushes had the highest mean concentrations of nitrates and phosphates.

In addition to pressures due to nutrient enrichment of water, petrifying spring communities were also found to be vulnerable to other pollutants (for example, sulphates), as well as to alterations to the pattern of water flow, inappropriate grazing levels (both undergrazing and overgrazing), physical damage (for example, deepening of drains), recreational activities and the impact of non-native species (in particular, the inappropriate siting of conifer plantations).

Measurements of the accumulation rate of tufa found that, on average, tufa cascades increase in height by 2.05 cm per year; the presence of *Palustriella commutata* is associated with increased deposition rates. Very rapid accumulation rates were measured locally; the fastest-growth rate recorded was in excess of 13cm per year and took place in the presence of the green alga, *Vaucheria* species.

Algae were not systematically sampled, but the red alga *Chroothece* sp. was recorded for the first time in Ireland; it was found in three coastal petrifying springs in Counties Clare, Dublin and Antrim.

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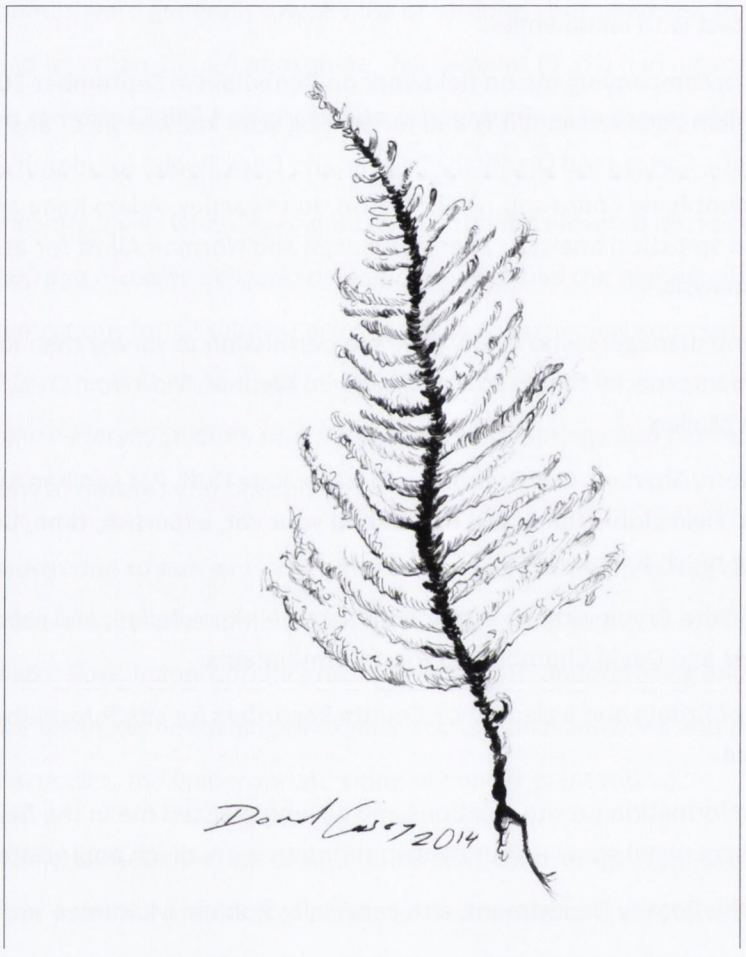
In memory of my Mother, Bessie (Elizabeth Ovington, 1924 - 2008)
and my Father, Ernest Lyons, who died in his 100th year
during the time of writing this thesis (February 2014).



Palustriella commutata shoot by Dónal Casey 2014

See, I am doing a new thing!
Now it springs up; do you not perceive it?
I will turn the desert into pools of water,
and the parched ground into springs.

Isaiah 43:19, 41:18

Abbreviations

BSBI	Botanical Society of Britain and Ireland
EPA	Environmental Protection Agency, Ireland
EQS	Environmental Quality Standard (threshold values set for certain substances in relation to assessing water quality under the Water Framework Directive).
ISA	Indicator Species Analysis
MC	Membership coefficient (%) indicates how strongly a sample is associated with a Fuzzy Cluster group.
NPWS	National Parks and Wildlife Service, Ireland
NVC	National Vegetation Classification of Great Britain (Rodwell 1997, 1998a, 1998b, 1998c, 2000)
SAC	Special Area of Conservation, designated under the Habitats Directive
SCS	Sørensen Coefficient of Similarity
s.l.	Sensu lato (in the broad sense)
s.s.	Sensu stricto (in the strict sense)
ssp.	Subspecies
p.p.	Pro parte (in part)
PQ	Permanent quadrat reference codes
PS	Petrifying spring site reference codes
QL	Quadrat reference codes
TB	Reference codes for bars installed for measuring tufa accumulation rates
VC	Vice-county; botanical divisions of which there are 40 on the island of Ireland (see, for example, Scannell & Synnott 1987 or Hill *et al.* 2008)
WS	Water sample reference codes

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1. Introduction

1.1 Petrifying Springs

Petrifying springs are lime-rich water sources which deposit tufa (or travertine, see below). The emerging spring water is rich in carbon dioxide and dissolved calcium carbonate. On contact with the atmosphere, carbon dioxide is outgassed and calcium carbonate is deposited as tufa. The resulting ecological conditions, with high pH and constant inundation by water and deposition of precipitated calcium carbonate, constitute a challenging environment for plants and animals to colonise, and the communities associated with petrifying springs are therefore highly specialised.

In the context of this study, there are two main concepts involved in defining what constitutes a petrifying spring: firstly, the formation of tufa, by which the habitat can be considered to be 'petrifying' and secondly, the presence of *Cratoneurion* vegetation, the plant community type most closely associated with petrifying springs in the literature. A more recent concept enshrined in the Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora) is that of the Annex I Priority Habitat 'Petrifying Springs with tufa formation (*Cratoneurion*) 7220', which brings together both the geochemical and vegetation concepts. But while this title (and the legal interpretation that accompanies it) encapsulates most of the habitat examples considered relevant for inclusion in this study, I have not felt strictly bound by it, so that by considering a broader range of related site types that presented opportunities for study, these definitions might be enhanced, rather than the study being constricted to suit the definitions. Therefore, I did not limit my investigations to springs, but included rivers, streams and waterfalls if they were tufa-forming; I looked at tufa-forming springs and seepages that did not necessarily support *Cratoneurion* vegetation; and I included a small number of examples of *Cratoneurion*-type vegetation at locations where there was little or no tufa.

1.1.1 Specialised, complex and threatened habitats

Petrifying springs are complex habitats which provide specialised niches for a species-rich assemblage of both flora and fauna (Cantonati 2006). They typically consist of a variety of microhabitats which enable species with different requirements to coexist in close proximity. The ecological significance of springs is seldom confined to a point source; rather, there is often a continuum of intergrading hydrological conditions from the spring head, through a flushed slope and into small streams. Spring heads may be distinct point locations giving rise to small streams

immediately below the point of emergence, or water may seep to the surface in a more diffuse pattern over a larger area.

The broad spectrum of pH influence across wetland habitats has long been recognised in the distinction between various types, referred to, for example, as ombrotrophic bog, poor fen and rich fen, and the merits of classifying mire habitats on the source and chemical composition of their waters as opposed to their vegetation types has been widely debated (*e.g.* Du Rietz 1949, Sjors 1950, Malmer 1986, Damman 1995, Bridgham 1996, Sheehy Skeffington & O'Connell 1998, Wheeler & Proctor 2000, Økland *et al.* 2001, Doyle & Ó Críodáin 2003, Hrivnák *et al.* 2008). I have adopted the terminology and conventions of Wheeler & Proctor (2000):

- 'mire' encompasses wetlands on peat and related communities on mineral soils;
- 'fen' refers to base-rich mires;
- 'oligo-', 'meso-' and 'eutrophic' denote nutrient levels (especially nitrates and phosphates), not base-richness (metallic cations and pH);
- 'small sedge fens' are oligo- to mesotrophic fens, with an open field layer of small, calcicole sedges, forbs and brown mosses; (the phrase 'brown mosses' refers loosely to a group of large, pleurocarpous mosses, especially belonging to the genera *Scorpidium, Campylium, Palustriella, Hamatocaulis, Tomentypnum* and *Calliergonella* (Porley & Hodgetts 2005));
- in the context of the present study, 'soligenous small sedge fens' belonging to the phytosociological alliance *Caricion davallianae* Klika 1934 constitute the fen type of greatest relevance; (for brevity, I have shortened it to 'small sedge fens', and in some places used the term 'rich-fen' to mean 'soligenous small sedge fens' sensu Wheeler & Proctor 2000;)
- 'springs' are strong, localised discharges of groundwater, from which the water may trickle downslope as a more or less well-defined 'flush';
- springs, flushes and fens form as a continuum and the distinction between flush and fen is physiognomic rather than floristic.

Petrifying springs represent extreme habitats at the upper end of the spectrum in terms of both pH and minerotrophic groundwater influence. The highly calcareous nature of such habitats exerts strong influences and limitations on their floristic composition (*e.g.* Webb & Hart 1945, Clymo 1962, Jeffrey 1987).

Hydrogeography, topography, landuse and climate have been identified as key factors to the distribution and ecological well-being of wetland habitats including petrifying springs (JNCC 2004,

2009). Mires have suffered devastating impacts due to intensification of landuse during the latter half of the twentieth century and since, and they have declined sharply in extent. Species and entire wetland habitats have declined in range due to drainage, alteration of water levels and eutrophication of waters (*e.g.* Fojt & Harding 1995, Preston & Croft 2001, Cusell *et al.* 2013). Changes in farming methods and the abandonment of traditional agricultural practices have also had far-reaching negative impacts (*e.g.* Wheeler 1988, Hájková 2009). Bryophyte communities, which typically dominate petrifying spring vegetation, are useful indicators of water quality (Ceschin 2012).

1.1.2 Legal context

The Habitats Directive, transposed into Irish law by S.I. No. 94/1997 European Communities (Natural Habitats) Regulations, 1997, recognises the ecological significance and vulnerability of petrifying springs by designating them as a priority habitat. An important stipulation within the habitats directive manual is that 'in order to preserve this habitat of very limited expanse in the field, it is essential to preserve its surroundings and the whole hydrological system concerned' (Commission of the European Communities 2003).

Under Article 17 of the Habitats Directive, member states are required to report on the conservation status of species and habitats every six years. The first such conservation status assessment on petrifying springs was compiled from earlier reports and desk surveys, drawing largely on data on fens in Ireland, and on existing field records of the moss species characteristic of petrifying springs (Hammond 1979, Crushell 2000, Foss 2007a, 2007b, National Parks and Wildlife Service 2008). The second conservation status assessment was prepared as part of the present project (Lyons & Kelly 2013).

Petrifying springs fall under the remit of the Water Framework Directive (Directive 2000/60/EC) as groundwater dependent terrestrial ecosystems (Curtis *et al.* 2009, Kimberley *et al.* 2013); their ecological significance is recognised under this legislation and there is a legal requirement to maintain or improve the status of the groundwaters with which they are fed.

1.2 Tufa: formation, significance and types

1.2.1 Tufa and travertine

Recent and historical literature contains an array of terms describing deposits formed from lime-rich waters along with a diverse range of definitions of these terms. The complexities of the deposition process and the variety of resulting deposit types, the particular focus of individual investigators and the historical development of the study of these processes all contribute to the varied and at times conflicting terminology.

In contemporary studies, the term 'tufa' is frequently applied to cool water deposits of highly porous or 'spongy' freshwater carbonates rich in microphytic and macrophytic growths, leaves and woody tissue (Pedley 1990). 'Tufa' has been applied in this sense, for example, to deposits in Spain (Arenas *et al.* 2000, 2014, Pedley *et al.* 2003, Vázquez-Urbez *et al.* 2010, Auqué *et al.* 2014), the Mediterranean region (Pedley 2009), the Eastern Alps (Sanders *et al.* 2011), Turkey (Glover & Robertson 2003), Australia (Wright 2000, Forbes *et al.* 2010 and Keppel *et al.* 2011) and Brazil (Corrêa et al. 2011).

The degree of lithification of deposits to which the term tufa is applied varies. Ford and Pedley (1996) apply it to all cool, freshwater, low-magnesium carbonates, regardless of the degree of lithificiation, whereas according to Pentecost (1993) 'calcareous tufa' describes poorly consolidated deposits while 'travertine' is used for the harder, more resilient deposits. However, Pentecost goes on to point out that it is impractical to separate the terms since wide variations in hardness and porosity occur even within a single formation. He therefore adopts the term 'travertine' to cover all deposits irrespective of their durability or porosity.

Pentecost (2005) defines travertine as:

"A chemically-precipitated continental limestone formed around seepages, springs and along streams and rivers, occasionally in lakes and consisting of calcite or aragonite, of low to moderate intercrystalline porosity and often high mouldic or framework porosity within a vadose or occasionally shallow phreatic environment. Precipitation results primarily through the transfer (evasion or invasion) of carbon dioxide from or to a groundwater source leading to calcium carbonate supersaturation, with nucleation/crystal growth occurring upon a submerged surface."

This definition emphasises reactions involving carbon dioxide and a calcium bicarbonate solution leading to precipitation of calcium carbonate ($CaCO_3$) in a non-marine setting. Most travertines form where groundwater rich in carbon dioxide dissolves carbonate rocks as it travels below

ground. Upon emergence at a spring point, carbon dioxide is lost to the atmosphere causing the deposition of the dissolved carbonate. This may be summarised as follows:

$$Ca^{2+} + 2(HCO_3)^- \leftrightarrow CaCO_3 + CO_2 + H_2O$$

A higher partial pressure of CO_2 below the ground surface (due principally to soil respiration or in some cases tectonic activity) leads to elevated levels in ground water and facilitates dissolution of $CaCO_3$. Conversely the lower partial pressure in the atmosphere contributes to subsequent deposition of solutes.

Other less common processes of travertine formation may occur, for example where atmospheric carbon dioxide reacts with hyperalkaline groundwater (Pentecost 2005), hence the inclusion of the possibility of invasion of carbon dioxide in Pentecost's definition above; this process is not relevant to the present study.

Meteogene and thermogene travertines

Pentecost & Viles (1994) and Pentecost (1995, 2005) distinguish two major geochemical categories of travertine based on the origin of the carrier carbon dioxide. Meteogene travertines are formed where the carbon dioxide originates in the atmosphere. Thermogene travertines derive their carbon dioxide predominantly from thermal processes deep below the surface of the Earth in tectonically active regions. Italy and Turkey contain many of the active European thermogene travertines (Pentecost 1995); none are known from Ireland.

Diagenesis

Diagenesis refers to changes to a rock subsequent to its original formation. In travertines, these may be derived from recrystallization of primary precipitates or by addition of secondary coatings and they provide an added dimension to the changing microenvironment (*e.g.* Golubić *et al.* 2008). This further complicates the distinction between 'travertine' and 'tufa'; Pedley (1990) refers to travertine as diagenetically altered tufa which has been infilled by later deposition.

Terminology adopted in this study

In this investigation of Irish deposits, the term 'tufa' is used throughout. Tufa is widely understood by ecologists and naturalists in the context of Irish wetland habitats to mean highly porous or poorly consolidated calcium carbonate deposits. The harder, more resilient deposits often implied in common usage by the term 'travertine' are not known to occur in Ireland.

Pentecost (2005) notes that 'tufa' is commonly applied to the soft, poorly consolidated deposits that abound in the British Isles. He abandons use of the term tufa in the context of reviewing, classifying and comparing deposits from widely differing regions of the world. His unambiguous definitions enable the clear demarcation of types of deposits from very different settings. However, within the relatively narrow range of spring types and environmental conditions encountered in Ireland, it seems unnecessary and potentially confusing to adopt the term 'travertine' in this study. Irish deposits of tufa fall within the category 'meteogene travertine' as defined by Pentecost (1995, 2005).

1.2.2 Abiotic versus biotic controls

The intimate association of biota with tufa has long given rise to speculation about the role of living organisms in deposition processes (*e.g.* Praeger 1904, Emig 1918). In a series of investigations of calcifying cyanobacteria and mosses, Pentecost (1978, 1996) and Pentecost & Franke (2010) estimated that only 1-14% of deposition could be attributed to removal of carbon dioxide by photosynthesis, 10-20% occurred through evaporation and 70-80% was caused by gas evasion (outgassing of CO_2 to the atmosphere to equilibrate partial pressure). Experimental comparisons of dark and light conditions in a tufa-forming stream found no difference in deposition rate between the two conditions, demonstrating a negligible effect by photosynthesis (Pentecost & Coletta 2007). Investigations of waterfall tufa formations (Zhang *et al.* 2001, Chen *et al.* 2004) showed that abiotic factors (aeration, jet-flow and low-pressure effects due to hydrological changes) greatly accelerate CO_2 outgassing and are the predominant driving force of precipitation in this setting.

However, mesocosm flume experiments conducted by Pedley *et al.* (2009) demonstrated that tufa precipitation could be induced in the laboratory using untreated natural river water, while sterilised river water produced virtually no deposition. They concluded that deposition was closely associated with extracellular polymeric substances produced by a prokaryote-microphyte biofilm.

Studies on the travertine formations of Plitvice, Croatia (Emeis *et al.* 1987, Golubić *et al.* 2008) elucidated the role of biofilms in carbonate precipitation. Microorganisms (especially cyanobacteria and diatoms) overgrow older, non-photosynthetic moss stems and debris such as detached leaves and branches. Mucous excretions from these microorganisms form a sticky mat, trapping seed crystals of calcite which act as nucleation sites upon which further deposition can occur, while bryophytes provide an architectural framework for the deposit.

More recent investigations (*e.g.* Keppel *et al.* 2011, Manzo *et al.* 2012) also showed that no precipitation took place where the biofilm was absent and research by Shiraishi *et al.* (2008) indicated that photosynthesis was a crucial mechanism to overcome the kinetic barrier for calcite precipitation, even in highly supersaturated settings.

1.2.3 Global distribution of deposits

Tufa and travertine deposits are widespread on a global scale. They have been found on all continents except Antarctica (Viles & Pentecost 2008), forming under a wide range of climatic regimes from cool temperate to semi-arid (Ford & Pedley 1996). Pentecost (1995) reviewed the deposits of Europe and Asia Minor and Ford & Pedley (1996) provided a review of deposits worldwide. Most are Quaternary deposits, though some older examples are known, for example Lower Permian deposits of the Slawkow Graben, Poland (Szulc & Cwizewicz 1989). Meteogene deposits at Antalya, Turkey cover an area of some 600 km^2 and are up to 250m thick, forming one of the largest and thickest deposits known worldwide (Glover & Robertson 2003).

Meteogene deposits are rare above latitude 58°N and in regions where the mean annual air temperature is below 5°C. A significant positive correlation exists between mean air temperature and travertine deposit thickness, since higher temperatures increase soil respiration and lead to greater degassing of emerging waters, more evaporation and higher photosynthetic rates of aquatic plants, all of which enhance travertine deposition (Pentecost 1995).

1.2.4 Palaeoenvironmental importance

Organic remains, stable isotopes and trace elements within travertine deposits are an important source of palaeoclimatic, palaeohydrological and other palaeoenvironmental information (*e.g.* Carthew & Drysdale 2003, Pentecost 2005, Andrews 2006, Corrêa *et al.* 2011). According to Pedley (2009), tufa, travertine and speleothem deposits (*i.e.* formed in unlit conditions, such as caves) in Mediterranean karstic landscapes hold the key to understanding Quaternary environmental change within that entire region. Studies of Irish deposits containing fossil molluscs, ostracods and pollen have contributed to our knowledge of the post-glacial colonisation of Ireland (Preece & Robinson 1982, Preece *et al.* 1986).

1.2.5 Tufa types

Fabric and Morphology

Tufa deposits vary in their fabric and morphology on a range of scales, from microscopic to geomorphological or landscapes, and the schemes for classification of facies vary accordingly.

Microfabric characters (calcite and aragonite fabrics, studied in thin sections and by scanning electron microscope) include textural features such as grain size, grain shape and relationships between adjacent mineral grains. The mesofabric of tufa can be seen with the naked eye in hand specimens. Important characteristics at this scale are porosity and laminations which arise due to physico-chemical, biotic and seasonal influences. Microfabric and mesofabric of tufa have been investigated in numerous studies (*e.g.* Rainey & Jones 2007, Golubić *et al.* 2008, Pedley 2009, Sanders *et al.* 2011 and Keppel *et al.* 2011).

Geomorphological classification

The macrostructure of deposits is of greatest relevance to the present study. Various attempts have been made in the past to classify deposits according to their geomorphology and setting. Ford & Pedley (1996) proposed four end-members of a continuum of tufa formation types: fluvial barrage, lacustrine, paludal and perched springline tufas. Pentecost & Viles (1994) placed travertines into two sub-groups: authochthonous (formed *in situ*) and allochthonous (formed *ex situ* from erosional products of earlier deposits). Authochthonous deposits were divided into eight categories which were further described and illustrated in Pentecost 1995 and 2005 (Fig. 1.1 below). This scheme has been adopted for the present study. It is readily applicable in the field and gives a useful way of distinguishing between deposits in various topographical settings.

The tufa formation categories relevant to Irish habitats are summarised in Table 1.1. While these categories in their most typical forms are clearly distinguishable from one another, intergrading forms are common and many locations contain a complex mosaic of deposits with different morphological characteristics.

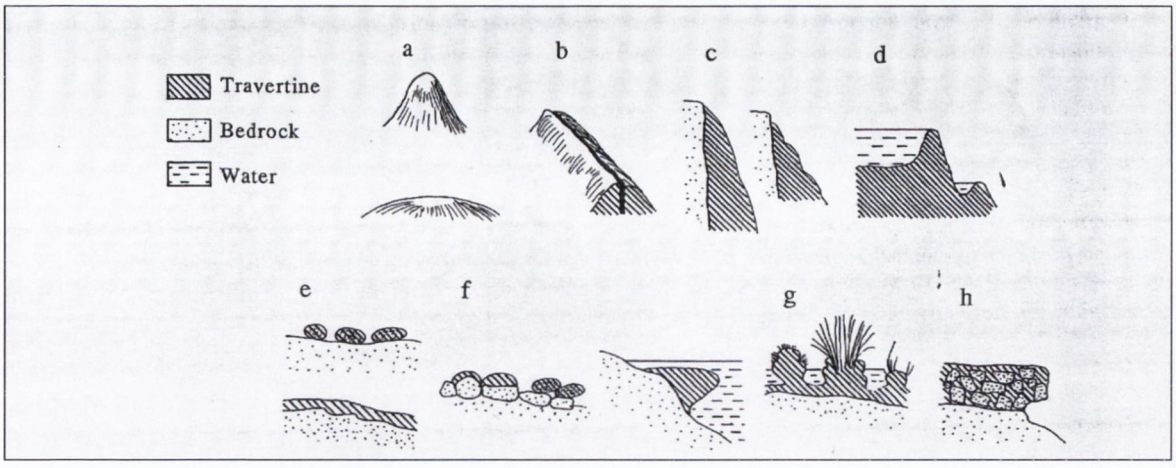


Fig. 1.1: Travertine morphologies (a) mounds; (b) fissure ridge; (c) cascades; (d) dam; (e) stream crust with oncoids; (f) lake crust with oncoids; (g) paludal deposit; (h) cemented rudite (not to scale). Reproduced from Pentecost (1995).

Table 1.1: Geomorphological classification of tufa formation types occurring in Ireland (adapted from Pentecost & Viles 1994, Pentecost 1995, 2005; photographs located at end of Chapter 3).

Category	Description
Cascade	Developing on steep slopes at varying distances from the water source; characterised by massive, frequently complex build-ups. (Generally corresponding to the 'perched springline' model of Ford & Pedley 1996, Pedley 1990 and Pedley *et al.* 2003) (*e.g.* Photos 3.1, 3.4, 3.5, 3.7, 3.14, 3.17).
Dam	Similar to cascades but forming along streams and rivers and causing the impoundment of water behind a tufa crest. (*e.g.* Photo 3.16).
Stream crust	Sheet-like deposits forming in streams of intermediate to low gradient; these may merge with cascades (*e.g.* Photos 3.34 and 3.44).
Paludal	Formed in low gradient mires where tufa accumulates around the bases of plants, often surrounded by carbonate muds (*e.g.* Photos 3.21, 3.23 and 3.30).
Cemented rudites	Gravels etc. cemented by tufa; often found on coasts where spring water seeps onto shingle banks (*e.g.* Photo 3.1).
Oncoids/ooids	Unattached, coated grains (<1mm up to 30 cm); the cortex may consist of biotic or abiotic particles, such as stones or plant fragments (*e.g.* Photo 3.25 and 3.36).

1.3 Historical context

Origins of terms

The term 'tufa' is derived from the Latin '*tofus*' mentioned in Plinius' Natural History. It is an ambiguous term which seems to have been applied to a range of soft rocks (Pentecost 2005). According to Pedley (2009), '*tophus*' was used commonly by the Romans to indicate a whitish and powdery rock, not always a freshwater carbonate, as it also included rocks of volcanic origin. Hence, a distinction was subsequently made between 'calcareous tufa' and 'volcanic tuff' (Ford & Pedley 1996). The term 'travertine' originates from *lapis tiburtinus* (Tibur stone, later *lapis Travertinus*) quarried near Rome for building works since the Classical Period (Pentecost 2005). The town of Tivoli, formerly known as Tibur, overlooks the quarries and much of classical Rome is built from travertine quarried here.

A note on some other terms

Calcareous tufa is the equivalent of the German term '*Kalktuff*' (*e.g.* Pedley 1990, Pentecost 2005 and Golubić *et al.* 2008), the French '*tuf calcaire*' (Pentecost 2005) and the Croatian '*sedra*' (Golubić *et al.* 2008). '*Travertino*' in Italian literature includes tufa and also hydrothermal deposits (Pedley 1990). In modern Italian '*tufo*' is used for volcanic deposits (Pentecost 2005). '*Sinter*', which originated in Germany for the dross formed by smelting iron, has occasionally been used to describe travertine (Pentecost 2005). Ford & Pedley (1996) suggest this term should be restricted to siliceous hot spring deposits. The term '*calc-sinter*' has also been used for calcareous tufa (Pentecost 2005).

Early habitat descriptions

Petrifying springs have long been recognised as intriguing natural or semi-natural features and the term 'petrifying spring' was in use as early as the mid-17th Century (Anon. 1665-1666). Much debate took place about the petrifying qualities of Lough Neagh during the 17th and 18th centuries (*e.g.* Smyth 1685, Nevill 1713, Simon 1747); most concerned fossilised wood washed into the lake by ancient rivers (Praeger 1939), but 'petrified potatoes' described by Buckland (1846) were, in fact, littoral oncoids (Pentecost 2005). Gilks (1735) described 'petrefactions' near Matlock Bath and he was clearly impressed by what lay before him:

> In one Place there is an Ivy creeping along the Rock, part of it intirely petrified, another part only incruſted, and a third ſtill vegetating. In another Place is a Hazle-tree, the Root whereof compoſes a Part of this petrified Mountain, the Branches ſome petrified, and ſome tenderly incruſted. As theſe are changed, others ſpring up, and in Time will undergo the ſame Fate. In ſhort, nothing in Nature can give a more clear Idea, or more beautiful Repreſentation, of the whole Buſineſs of Petrefaction, than a curious Obſerver will ſee, and frame in his Mind from this Mountain.

Praeger (1904) summed up the tufa formation process in a note on deposits in Knocknarea Glen, Co. Sligo (see Chapter 2). Emig (1918) described the tufa-forming behaviour of *Didymodon tophaceus* and *Philonotis calcarea* in waterfalls in the Arbuckle Mountains, Oklahoma, while Taylor (1919) reported *Brachythecium rivulare* and *Cratoneuron filicinum* as tufa formers.

Pentecost (1991) reported the long established tradition of suspending objects, including teddy bears and various items of clothing, beneath dripping sheets of water at some British springs until they were 'turned to stone'.

1.4 Selection of sites for field survey

The early stages of the project entailed drawing up a list of possible sites for field survey. This list was derived from various sources: the earlier conservation status report (Foss 2007a); NPWS site files (especially those relating to SACs for which petrifying springs are a qualifying interest, Appendix I); literature searches; and conversations with experts in various fields, including BSBI Vice-County recorders, NPWS rangers, botanists, ecologists, geologists, local naturalists and land owners/managers. The final list contained 174 sites (summarised in Table 1.2).

110 sites (63%) were visited and surveyed. Nine sites visited were not surveyed because the habitat types found were borderline, for example with only the faintest trace of tufa, or the site visit was inconclusive; *i.e.* while no relevant habitat was seen at the site, it was not possible to rule out the existence of petrifying habitats within the general area. A further seven sites visited were deemed to contain no relevant habitat. Given the dispersed nature of sites around the country, the uncertainty of their exact locations and the small size of many springs (and therefore the difficulty in locating them), it was not possible to visit all sites on the list in the time available during this project. Thirty-two sites were considered low priority for visiting because of a combination of lack of information on location, uncertainty about the relevance of the habitats they contained and/or because they were distant and most likely small or inaccessible. Thirteen

sites deemed worthy of investigation remained unvisited by the end of the fieldwork stage; some of these had been added to the list in the later part of the project. Site access was denied by the landowner at three sites.

Table 1.2: Sites considered for field survey

Number of sites	%	Outcome
110	63.2%	Visited and surveyed
9	5.2%	Visited; habitat type borderline / inconclusive
7	4.0%	Visited but relevant habitat not found
32	18.4%	Insufficient information on location or habitat type; not visited
13	7.5%	Potentially relevant sites not visited during this project
3	1.7%	Access denied by landowner
174	**100%**	**Total**

Of the sites surveyed, relevés were recorded at 73 sites (66% of those surveyed). At the remaining 37 sites, species lists and general notes were made, grid references were recorded and photographs were taken. The most common reason for not recording relevés was that the petrifying spring habitat was of very small extent and/or the habitat type was borderline (at 29 of these sites, *i.e.* 78%). Many of these locations were visited before field methods had been finalised – preliminary surveys of a wide range of sites were necessary to decide on appropriate methodologies – and a return visit was not considered worthwhile due to the small extent or borderline nature of the habitat. Three sites in the Burren (PS052, PS053, PS095, Appendix I) and one in the Slieve Blooms (PS072) were not revisited for more detailed study, as sites of these types were already well represented at other locations within the respective regions. One site was not revisited due to its inaccessible location (PS051.1), two were visited opportunistically after analysis of relevé data had commenced (PS090, PS098) and one small, atypical site had been destroyed prior to being revisited (PS010, tufa formed on the lock gates of the Grand Canal at Naas and removed during cleaning of the gates).

1.5 Thesis aims and structure

The primary aim of this study is to provide a greater understanding of petrifying springs as they occur in Ireland with respect to:

- the plant species that colonise petrifying springs
- differences within the habitat: sub-communities in different ecological settings
- the role of ecological characteristics, especially spring water composition, in influencing the flora
- dynamic process at work in the habitat, especially the rate of accumulation of tufa
- the threats and pressures to which the habitat is subjected
- the conservation status of the habitat.

In addition, this project seeks to make a contribution more widely, in circumscribing the vegetation of petrifying springs and elucidating the relationship of Irish petrifying spring plant communities to those elsewhere in Europe.

To this end, Chapter 2 contains a review of plant communities relevant to the collective understanding of what constitutes *Cratoneurion* vegetation and/or the petrifying spring habitat. Some of the related habitats into which petrifying springs typically grade are also briefly considered. Chapter 3 is a description of eight newly-defined plant communities of Irish petrifying springs. These were derived from statistical analysis of 186 relevés collected during this project. The findings show that communities defined on the basis of their floristic composition each have distinctive ecological characteristics. In Chapter 4, the newly-described plant communities of Irish petrifying springs are compared to the vegetation types reviewed in Chapter 2 and their relationships are discussed.

Chapter 5 contains an analysis of the composition of spring water of Irish petrifying springs. Data from Irish springs are compared to those reported from studies outside Ireland, differences in the composition of water between the eight plant communities are investigated, and the relationship between various water chemistry parameters and individual species is considered.

The impact of anthropogenic factors on the flora and conservation status of petrifying springs and the pressures and threats to which the habitat is subjected are discussed in Chapter 6.

Chapter 7 contains a study of some of the dynamic aspects of petrifying springs, in particular the rate of accumulation of tufa. Processes of recolonization of landslide sites are also examined.

Chapter 8 draws together the main conclusions of the project and makes recommendations for further studies.

1.6 Some notes on the text

Nomenclature

Nomenclature follows Stace (2010) for vascular plants, Hill *et al.* (2008) for bryophytes and John *et al.* (2011) for algae. The term 'graminoids' is used to refer to grasses, sedges and rushes; 'pteridophytes' contains ferns and horsetails; and 'forbs' includes all other herbaceous, vascular plants.

Vascular plants and bryophytes were recorded in all samples. *Chara* spp were included in the data set if determined to species; Dr C. Roden assisted with identification. Algae were not systematically sampled but, from time to time, samples were collected and sent to Dr C. Carter for identification.

The name *Drepanocladus revolvens* has frequently been applied in the literature. This name is problematic; it included *D. revolvens* var. *intermedius,* now known as *Scorpidium cossonii. S. cossonii* is of relevance in the present study, but *D. revolvens s.s.* is not. To avoid ambiguity, records for *D. revolvens* reported in the literature are omitted from the present study unless var. *intermedius* is specified.

Constancy Classes

The frequency with which species occur in groups of samples is denoted by Roman numerals: I = up to 20%, II = 21% to 40%, III = 41% to 60%, IV = 61% to 80% and V = 81% to 100%. 'Constant' species are those in constancy classes IV and V. In general, common or frequent species are those in class III, while species in class II are referred to as occasional and in class I as scarce (Rodwell 1998a).

Ground cover

Ground cover values for species and variables (such as tufa formation type) are estimated as a percentage of the area sampled. For individual relevés, they are an estimate of the proportion of the ground covered by the species or variable, made by eye at the time of recording the relevé. For plant communities, they are the mean of all samples in that group.

Probability Values

Asterisks denote p-values as follows: *** p-value <0.001; ** p-value <0.01; * p-value <0.05.

2. Petrifying Spring Communities: A Review

This chapter reviews the main contributions to our collective understanding of the plant communities of petrifying springs, and of what constitutes *Cratoneurion* vegetation. The *'Cratoneurion'* concept originated in the phytosociological approach to classifying plant communities, devised and advocated by Braun-Blanquet and others in central Europe, beginning in the early part of the 20th Century (*e.g.* Braun-Blanquet *et al.* 1932). Phytosociology is a hierarchical system of classifying vegetation types, using 'character species' which are relatively restricted or 'faithful' to a particular community and 'differential species' which discriminate between some but not all related communities. 'Companion species' are those which occur frequently in a community, but are not preferential to it. The hierarchical structure consists of associations grouped successively into alliances, orders and classes. Each community, or syntaxon, is named according to one or two of its typical species; associations are denoted by names containing the ending '-etum', alliances by the ending '-ion', orders by the ending '-etalia' and classes by the ending '-etea'. See Westhoff & van der Maarel (1978) and White & Doyle (1982) for further details. While some valid concerns have been raised about the approach (notably by Webb (1954)), there endures a robust framework for understanding, documenting and studying plant communities.

In this chapter, Section 2.1 contains a brief narrative of the earliest phytosociological descriptions of petrifying spring vegetation in Continental Europe up to 1956; at the end of that period, much of the earlier work was consolidated in Oberdorfer's first edition of Süddeutsche Pflanzengesellschaften (Oberdorfer 1957). Section 2.2 is a summary of the most relevant currently accepted syntaxa (including those introduced in the previous section). Section 2.3 looks at British studies of petrifying springs and related habitats prior to the publication of the NVC and concludes by outlining the relevant NVC communities. Section 2.4 contains a summary of Irish petrifying spring studies. The chapter concludes with the Habitats Directive interpretation of what constitutes the Annex I priority habitat 'Petrifying springs with tufa formation (*Cratoneurion*)' (Section 2.5).

2.1 Early vegetation studies

The vegetation type most closely associated with petrifying springs, both in the legal definition of the Habitats Directive and more generally in the ecological literature, is *Cratoneurion*. This term was first introduced by Koch in 1928; its definition was refined as studies from different geographical regions were conducted.

Much of the early work was carried out in Central Europe and therefore includes many species, most notably alpine species, absent from Ireland. Only the most important of these are mentioned in the account that follows, focusing on species most widely regarded as characteristic of the community; the emphasis is on establishing the background into which Irish petrifying springs can be placed.

The species composition of the communities described is summarised in Tables 2.1 and 2.2. Infrequent species have been omitted from these tables to focus on the main trends. Roman numerals are frequency classes and are given where these are published elsewhere in synoptic tables or where data from five or more samples are reported. (I=1-20%, II=21-40%, III=41-60%, IV=61-80%, V=81-100%).

2.1.1 *Cratoneurion commutati* (Koch 1928)

The vegetation type *Cratoneurion commutati* was first described by Walo Koch in his 1928 monograph 'Die höhere Vegetation der subalpinen Seen und Moorgebiete des Val Piora' (The upland vegetation of the subalpine lakes and moorland of the Val Piora). Koch defined this alliance (sometimes shortening the title to *Cratoneurion*) as fresh-water, lime-rich spring communities with frequent tufa formation, found especially in the montane and sub-Alpine zone, in which the ground layer consisted of mosses.

Koch placed the alliance *Cratoneurion* alongside the *Cardamineto-Montion* alliance, which comprises decalcified, cold water springs (Fig. 2.1a below). He also co-ranked it with the *Caricion fuscae* (Koch 1926) which consists mostly of acidophile, sedge-dominated associations but also contains the calcicole *Caricetum davallianae* which, Koch noted, forms a transition to the *Cratoneurion* alliance.

Koch described a single association within the *Cratoneurion* alliance, the *Cratoneureto-Arabidetum bellidifoliae*. This community had in part been referred to by other workers (*e.g.* Gams 1927) but had not been formally described. Koch acknowledged the difficulty in separating

this vegetation type from other communities, given its often small size and frequent juxtaposition with communities of very different ecological conditions.

The character species of the *Cratoneureto-Arabidetum bellidifoliae* were assigned by Koch as *Arabis soyeri* ssp. *subcoriacea*, *Carex frigida*, *Saxifraga aizoides* and *Palustriella falcata*[1]. He noted as very characteristic an often dense ground cover of the last species and the absence of species of the equivalent association of lime-poor springs and streams, the *Bryetum schleicheri. Arabis soyeri* ssp. *subcoriacea* (syn. *Arabis bellidifolia* ssp. *jacquinii*) is confined to the Alps and W. Carpathians (Tutin *et al.* 1993). Companion species in the *Cratoneureto-Arabidetum bellidifoliae* include *Deschampsia cespitosa, Agrostis stolonifera, Equisetum variegatum, Tussilago farfara* and *Bryum pseudotriquetrum* (Table 2.1 below). While Koch assigned character species for the association, none were allocated to the overall *Cratoneurion commutati* alliance.

1 The names '*Cratoneuron commutatum Hedw. var. falcatum* (Brid.)' (Koch 1928, p.155) and an alternative used elsewhere in the same paper, *Cratoneuron falcatum* Brid. (Koch 1928, p.156), are somewhat imprecise in the nomenclature and stated authority. However, there is no doubt that they refer to *Palustriella falcata* (Brid.) Hedenäs (T. Blockeel, *pers. comm.*), accepted synonyms of which are *Cratoneuron commutatum* (Hedw.) G.Roth. var. *falcatum* (Brid.) Mönk. and *Hypnum falcatum* Brid.

Table 2.1: Species composition of associations in the alliance *Cratoneurion* in Continental Europe.

	Cratoneuretum falcati								Crat. com.	Cratoneuretum filicino-commutati		Cratoneureto-Saxifragetum aizoidis		Coch. pyr.	Pel. end.
	Gams 1927	Koch 1928	Br.-Bl. 1931	Br.-Bl. 1948	Br.-Bl. 1949	Oberd. 1977	Br.-Bl. 1978	Surina 2005	Aich. 1933	Kuhn 1937	Oberd. 1977	Nordh. 1943	Dahl 1956	Oberd. 1977	Hadač 1983
CHARACTER SPECIES															
Palustriella falcata	✓	V Chr	✓	V Chr	Chr	V Chr	IV	V				III			
Palustriella commutata			✓		Chr	I	II		V	✓	V Chr	IV		V Chr	V
Philonotis calcarea			✓	II Chr	Chr	II	IV	III			II			IV	I
Arabis soyeri ssp. subcoriacea	✓	IV Chr	✓		Chr	I Chr	V				I				
Saxifraga aizoides	✓	V Chr	✓	III	Cmp	I	III	III	II			III	✓		
MONTIO-CARDAMINETEA															
Brachythecium rivulare				II		I	I				II			II	V
Bryum pseudotriquetrum		III			Cmp	III	II			✓	III	V	✓	III	N. #1
Pohlia wahlenbergii				IV		I	I						✓		
Cardamine amara		II		II		I	II				I			I	
Caltha palustris (inc. var. minor)	✓			II		I	I				I			I	
Epilobium alsinifolium	✓		✓	V		II	III	IV				IV			
Saxifraga stellaris	✓	II	✓	I	Cmp	IV	IV	III							
BRYOPHYTES															
Aneura pinguis	✓				Cmp		I				I		✓	I	
Campylium stellatum											I			III	V
Conocephalum conicum										✓	II				II
Cratoneuron filicinum						I				✓	II			II	I
Eucladium verticillatum									I		II				II
Hymenostylium recurvirostrum										✓	I				
Leiocolea bantriensis	✓														
Orthothecium rufescens							I		I						
Palustriella decipiens						I	I						✓		
Pellia endiviifolia											II				IV
Philonotis fontana	✓					I						II	✓		
Platyhypnidium riparioides										✓	I				
Tomentypnum nitens														II	
VASCULAR PLANTS															
Adiantum capillus-veneris															
Agrostis stolonifera		V	✓	IV	Cmp	II	V				II			II	III
Aster bellidiastrum	✓	II	✓			I	III		V		I				
Carex flacca						I			II		II			II	
Carex lepidocarpa									I						
Cochlearia pyrenaica														V Chr	
Crepis paludosa							I		III		I	II			
Deschampsia cespitosa	✓	V	✓	III	Cmp	II	V	II	II		I	IV	✓	I	
Eleocharis quinqueflora	✓														
Equisetum telmateia											I				
Equisetum variegatum		III					III					II			
Eriophorum latifolium	✓														
Geranium robertianum										✓	II				
Lycopus europaeus															III
Parnassia palustris								III	I			I			
Pinguicula alpina	✓							I	V						
Pinguicula vulgaris						I					I				
Polygonum viviparum	✓		✓			I	III	I				II	✓		
Scrophularia umbrosa															III
Selaginella selaginoides								I	I						
Thalictrum alpinum												I	✓		
Tussilago farfara		II	✓		Cmp		II		IV			IV			

Crat. com. = *Cratoneurietum commutati*; Coch. pyr. = *Cochleario pyrenaicae-Cratoneuretum commutati*;
Pel. end. = *Pellio endiviifoliae-Cratoneuretum commutati;*
Authors (in sequence, as above): Gams (1927); Koch (1928); Braun-Blanquet (1931, 1948, 1949); Oberdorfer (1977); Braun-Blanquet (1978); Surina (2005); Aichinger (1933); Kuhn (1937); Oberdorfer (1977); Nordhagen (1943); Dahl (1956); Oberdorfer (1977); Hadač (1983).

Frequency: I=1-20%, II=21-40%, III=41-60%, IV=61-80%, V=81-100%; ✓ = fewer than five samples or frequency not stated

Chr = character species for associations; Cmp = companion species

N. #1: Value missing from table (Hadač 1983, p358) but species is listed in text for this association (p353)

Fig. 2.1: Class, Order and Alliance relationships relating to *Cratoneurion* vegetation

(a) Classification of Koch (1928)

All.	**Cardamineto-Montion** *Decalcified, cold water springs*	**Cratoneurion** *Lime-rich springs, frequently tufa-forming*	**Caricion fuscae** *Sedge-dominated vegetation*	
			Calcicole	Calcifuge
Ass.	1. Cardaminetum amarae 2. Bryetum schleicheri	1. Cratoneureto-Arabidetum bellidifoliae	1. Caricetum davallianae	1. Caricetum fuscae alpinum 2. Eriophoretum scheuchzeri 3. Trichophoretum caespitosi alpinum

Transitional

(b) Classification of Braun-Blaunquet (1949)

Class	**Montio-Cardaminetea Br.-Bl. et Tx. 1943**		
Ord.	**Montio-Cardaminetalia Pawlowski 1928** Character species: *Cardamine amara, Epilobium alsinifolium, Saxifraga stellaris, Caltha palustris, Deschampsia cespitosa* var. *alpina, Bryum pseudotriquetrum, Pohlia wahlenbergii, Palustriella decipiens*		
All.	**Cardamineto-Montion Br.-Bl. 1925** Neutral to acid springs Character species: *Rhizomnium punctatum, Brachythecium rivulare, Stellaria uliginosa*	**Cratoneurion commutati W. Koch 1928** Calcareous springs	**Endocarpion all. nov.** Submerged community of mosses, lichens and algae
Ass.	**1. Cardaminetum amarae (Rübel 1912) Br.-Bl. 1926** **2. Bryetum schleicheri Br.-Bl. (1921) 1926**	**1. Cratoneureto-Arabidetum bellidifoliae Koch 1928** *Palustriella falcata, P. commutata, Philonotis calcarea, Arabis soyeri* ssp. *subcoriacea*	**1. Endocarpeto-Schistidietum rivularis ass. nov.**

(c) Classification of Zechmeister and Mucina (1994) (selected alliances and associations only)

Class	**Montio-Cardaminetea Br.-Bl. et Tx. ex Klika et Hadač 1944 em. Zechmeister 1993** Class amended by fusing with the class *Adiantetea* Species: *Palustriella commutata, Cratoneuron filicinum, Brachythecium rivulare, Bryum pseudotriquetrum*		
Ord.	**Montio-Cardaminetalia Pawlowski 1928 em. Zechmeister 1993** Order amended by fusing with the order *Adiantetalia* Contains six alliances in total; only the three most relevant alliances are shown below		
All.	**Adiantion** (with *Eucladium verticillatum* and *Adiantum capillus-veneris*) Contains six associations	**Cratoneurion** (with *Philonotis calcarea* and *Saxifraga aizoides*) Contains four associations	**Caricion remotae** (with *Carex remota*) Contains six associations
Ass.	**1. Cratoneuretum commutati** (with *Didymodon tophaceus*) **2. Eucladio-Adiantetum** (with *Eucladium verticillatum, Adiantum capillus-veneris* and *Hymenostylium recurvirostrum*)	**1. Cratoneuretum falcati** (with *Palustriella falcata*) **2. Cratoneuro-Hygrohypnetum luridi** (with *Hygrohypnum luridum*)	**1. Pellio-Chrysosplenietum oppositifolii** (with *Chrysosplenium oppositifolium*)

2.1.2 Early phytosociological studies in Central & Northern Europe 1927-1956

The year prior to Koch's Val Piora survey, Gams (1927) recorded relevés from tufa springs and lime-rich seepage channels on Les Follatères, Dent de Morcles, in the Swiss Alps. He described three relevés (above 2000m) as typical *Cratoneuretum falcati*. These contained *Palustriella falcata*, *Saxifraga aizoides* and *Arabis soyeri* ssp. *subcoriacea* (Table 2.1). He also recorded relevés from springs at lower altitudes (below 2000m) with *Palustriella commutata, Hymenostylium recurvirostrum* and *Philonotis calcarea,* but did not provide a syntaxonomic classification. He pointed out that there was no satisfactory classification for Alpine and Subalpine spring communities and suggested they might be divided according to the dominant life form: mosses, grasses, perennial forbs or small shrubs.

Gams did not specify an alliance for the *Cratoneuretum falcati*, and Koch's *Cratoneurion commutati* endures as the higher syntaxon to which tufa-forming springs belong. Gams' *Cratoneuretum falcati* is often regarded as synonymous with Koch's *Cratoneureto-Arabidetum bellidifoliae* and is sometimes the preferred association name, having been published first (*e.g.* Oberdorfer 1977).

In the decades that followed, the alliance *Cratoneurion commutati* was reported from a number of new locations in the Alps (*e.g.* Aichinger 1933, Braun-Blanquet 1949) and also from the Pyrenees (Braun-Blanquet 1948). Koch's circumscription of the *Cratoneurion commutati* was reiterated as springs of fresh, lime-rich water, dominated by mosses, often encrusted with lime and forming tufa (*e.g.* Braun-Blanquet 1949). In keeping with Koch, diagnostic species were assigned at association level (and order or class level) but not at alliance level.

The *Cratoneureto-Arabidetum bellidifoliae* association was the name adopted in some of these studies, typically at altitudes of 1800 – 2300m. Braun-Blanquet & Braun-Blanquet (1931) described it from Grossglockner, Austria, as clumps of *Cratoneuron* spp and sometimes *Philonotis calcarea,* soaked with cold spring water, dotted with phanerogams including conspicuous yellow cushions of *Saxifraga aizoides*. The authors chose to highlight the occurrence of *P. calcarea*, even though it was not present in any of their relevés. Later, it came to be regarded as a character species (Braun-Blanquet 1948, 1949).

Palustriella commutata was later added as a character species along with *P. falcata* (*e.g.* Braun-Blanquet 1949, Table 2.1). *Saxifraga aizoides* was more often considered a companion species than a character species (*e.g.* Braun-Blanquet 1948, 1949). Other frequently occurring companion species in these studies were *Tussilago farfara, Deschampsia cespitosa, Agrostis stolonifera* and

Bryum pseudotriquetrum. Spring vegetation from the Eastern Pyrenees was regarded as a depauperate version of the Alpine *Cratoneureto-Arabidetum bellidifoliae* (Braun-Blanquet 1948).

Nadig (1942) investigated the water chemistry of a spring in Engadin National Park, Switzerland, with *Cratoneureto-Arabidetum bellidifoliae* vegetation and found the pH 7.1 – 7.2[2]. The water was unpolluted; traces of nitrate were found (up to 0.5mg/l), but ammonia and nitrite were at levels below detection.

A new association within *Cratoneurion commutati*

A new association, the *Cratoneurietum commutati,* was added to the alliance by Aichinger (1933) in his study of the Karawanken Mountains on the Austrian – Slovenian border. *Arabis soyeri* ssp. *subcoriacea* was lacking but tufa was deposited. *Palustriella commutata* was the dominant species and alpine species such as *Pinguicula alpina* were frequent (Table 2.1). Aichinger pointed out that it was uncertain to what extent this association matched the *Cratoneureto-Arabidetum bellidifoliae* because of the small number of samples but they contained in common *Saxifraga aizoides, Deschampsia cespitosa, Aster bellidiastrum* and *Tussilago farfara*. Two noteworthy mosses occurred here: *Eucladium verticillatum* and *Orthothecium rufescens*, both in a 'very strongly tufa-forming' relevé. *Crepis paludosa, Parnassia palustris*, *Carex flacca, C. lepidocarpa* and *Selaginella selaginoides* were also present in Aichinger's relevés, recorded at lower altitudes (30 – 900m above sea level) than the *Cratoneureto-Arabidetum bellidifoliae* surveys above.

A new alliance: *Cratoneureto-Saxifragion aizoidis*

Nordhagen (1937) placed lime-rich, upland Norwegian spring vegetation in a new alliance, the *Cratoneureto-Saxifragion aizoidis,* which he regarded as an impoverished version of Koch's *Cratoneurion commutati*. He described a single association, the *Cratoneureto-Saxifragetum aizoidis* (Table 2.1), but used subgroups within this association to distinguish *P. commutata*-dominated stands with *Epilobium alsinifolium* from vegetation with *Palustriella falcata, Saxifraga aizoides, Polygonum viviparum* and *Equisetum variegatum* (Nordhagen 1943, see Fig. 2.2 below).

Nordhagen (1937) expressed reservations about the name *Cratoneurion commutati*, since *Cratoneuron* springs occur in the lowlands with a very different species complement to that of the alpine or subalpine zone. Later (1943), he applied the name *Cratoneurion* to lowland, lime-rich,

[2] Data from numerous samples analysed between 1934 and 1937 showed a pH range 6.9 to 8.1, but most values were in the range 7.1-7.2.

Norwegian spring vegetation whereas he referred the upland equivalent to the alliance *Cratoneureto-Saxifragion aizoidis.*

Dahl (1956) referred the upland spring vegetation (alt. 1050m) of Rondane, in south Norway, to Nordhagen's *Cratoneureto-Saxifragetum aizoidis* and noted that *Palustriella decipiens* replaced *P. commutata* (alt. 1050m) (Table 2.1).



Fig. 142. Gulsildre (*Saxifraga aizoides*). 7/10. Vanlig ved kjelder og i kortvoksne, artsrike fjellmyrer på kalk, glimmerskifer og fyllitt.

Fig. 2.2: *Saxifraga aizoides* illustrated in Nordhagen's 1943 monograph on Norwegian mountain pastures.

Unassigned vegetation

Kuhn (1937) provided species lists for tufa-forming springs in the Swabian Alps. Rather than using phytosociological nomenclature, he grouped these lists under the heading of '*Hypnum commutatum (*syn. *Palustriella commutata)* and *Cratoneuron filicinum* Communities'. In addition to these two species, *Hymenostylium recurvirostrum, Platyhypnidium riparioides, Bryum pseudotriquetrum* and *Conocephalum conicum* were also present. These samples were recorded at lower altitudes (approximately 600m above sea level) than earlier alpine studies; *Saxifraga aizoides* and *Arabis soyeri* ssp. *subcoriacea* were notably absent from the species lists (Table 2.1).

2.1.3 Synthesis up to 1956

These early studies provide the nucleus around which the alliance developed its identity. There was a tendency to assign diagnostic species at the level of association (and order or class) so that the unifying characteristics of the alliance were defined by abiotic factors (lime-rich, tufa-forming springs) rather than its species composition. For the most part, studies focused on high altitude sites and alpine species are prominent in the definition of the associations. Kuhn, however, provided some early insights into spring vegetation at lower altitudes.

2.2 Currently accepted phytosociological communities

A more comprehensive overview of lime-rich spring vegetation in Continental Europe emerged in the second half of the 20th Century. Some of the communities outlined above were retained or amended and new communities were described.

2.2.1 Class and Order structure

Traditionally, the alliance *Cratoneurion* falls within the class *Montio-Cardaminetea* Br.-Bl. et Tx 1943 and the order *Montio-Cardaminetalia* Pawlowski 1928, along with the *Cardamineto-Montion* Br.-Bl. 1925 alliance of neutral to acid springs (*e.g.* Braun-Blaunquet 1949; my Fig. 2.1b above). Species that are widely regarded as characteristic of this class and order are *Cardamine amara*, *Epilobium alsinifolium*, *Saxifraga stellaris*, *Caltha palustris*, *Bryum pseudotriquetrum* and *Pohlia wahlenbergii* (Braun-Blanquet 1948, 1949 and Oberdorfer 1957).

Maas (1959) undertook a revision of the phytosociological classification of spring vegetation, creating two orders within the class *Montio-Cardaminetea*, to distinguish the acidic to neutral springs of an amended *Montio-Cardaminetalia* from the calcareous, alkaline springs of a new order, *Cardamino-Cratoneuretalia*.

In a later revision of the class *Montio-Cardaminetea,* Zechmeister and Mucina (1994) abandoned Maas's division due to the scarcity of character species, retaining the *Montio-Cardaminetalia* as a single order in the class. They placed within it six alliances, including the *Cratoneurion*, *Adiantion* and the woodland *Caricion remotae* alliances (Zechmeister and Mucina 1994, Fig. 2.1c above).

2.2.2 Alliance *Cratoneurion commutati* W. Koch 1928

Character species of the alliance *Cratoneurion commutati* remain poorly defined. *Philonotis calcarea* is perhaps the species most consistently regarded as characteristic.

Initially, Oberdorfer (1957) assigned as alliance character species *Palustriella commutata, Cratoneuron filicinum, Eucladium verticillatum, Philonotis calcarea* and *Saxifraga aizoides*. Later on, however, most of these assumed more important roles at association level and he retained only *Philonotis calcarea* at alliance level (Oberdorfer 1977).

Zechmeister & Mucina (1994) designated *Saxifraga aizoides* (III), *Arabis soyeri* ssp. *subcoriaceae* (II), *Philonotis calcarea* (II) and *Equisetum variegatum* (I) as character species of the alliance, with the last-named differential from other alliances within the class. The low frequencies with which these species occur are indicative of the difficulties of assigning suitable species.

Maas (1959) assigned *Cratoneuron filicinum* and *Equisetum telmateia* as character species of lowland *Cratoneurion* springs. For montane to subalpine *Cratoneurion* springs, he designated *Palustriella commutata*, *Eucladium verticillatum* and *Saxifraga aizoides* as the character species. He advocated dropping *'commutati'* from the alliance epithet to embrace a broader species range.

2.2.3 Alliance *Adiantion* Br.-Bl. 1931

Braun-Blanquet (1931) reported this Mediterranean vegetation type from the south of France with *Adiantum capillus-veneris* and *Eucladium [verticillatum]*. It occurs on irrigated cliffs especially in damp, shallow recesses or 'half-caves' (Deil 1994). It overlaps strongly in species composition with the *Cratoneurion* and is tufa-forming (Zechmeister and Mucina 1994). *Adiantum capillus-veneris, Samolus valerandi, Eucladium verticillatum, Pellia endiviifolia, Conocephalum conicum* and *Gymnostomum* spp. are characteristic, often accompanied by *Hymenostylium recurvirostrum, Didymodon tophaceus, Palustriella commutata, Cratoneuron filicinum, Platyhypnidium riparioides, Pohlia wahlenbergii, Aneura pinguis* and *Preissia quadrata* (Deil 1994). While it has often been placed alongside other fern communities of cliffs and walls (*e.g.* Ivimey-Cook and Proctor 1966), Zechmeister and Mucina (1994) argued that it is better placed within the *Montio-Cardaminetea* spring communities.

2.2.4 Association *Cratoneuretum falcati* Gams 1927

Oberdorfer (1977) regarded the alpine petrifying spring association *Cratoneuretum falcati* Gams 1927 as synonymous with *Cratoneureto-Arabidetum bellidifoliae* Koch 1928, and gave precedence to the former name. Apart from the earlier publication date, *Arabis soyeri* ssp. *subcoriacea* (syn. *Arabis bellidifolia*) has a broad phytosociological range and is of low constancy within the association.

Braun-Blanquet (1978) on the other hand, retained an amended version of Koch's original name, the *Cratoneuro-Arabidetum bellidifoliae,* in an analysis of 35 relevés from calcareous alpine springs bordering *Caricetum davallianae* vegetation in Graubünden, Switzerland. He differentiated two sub-associations, the *cratoneuretosum commutati* dominated by *Palustriella commutata* and the *cratoneuretosum falcati* dominated by *Palustriella falcata*. Earlier studies had indicated that *Palustriella commutata* and *P. falcata* were, to some extent, separated altitudinally, with *P. falcata* at higher elevations (*e.g.* Gams 1927, Oberdorfer 1977). However, in these samples the species overlapped for most of their altitudinal range and, apart from the two dominant *Palustriella* species, there was no other distinction in species composition between the two subassociations.

Widely recognised character species of the *Cratoneuretum falcati* are *Palustriella falcata*, *Arabis soyeri* ssp. *subcoriacea* and *Saxifraga aizoides*. *Palustriella commutata* and *Philonotis calcarea* are also frequent along with character species of the order *Montio-Cardaminetalia*: *Saxifraga stellaris, Epilobium alsinifolium and Bryum pseudotriquetrum.* Companion species include *Tussilago farfara, Deschampsia cespitosa and Agrostis stolonifera*. Other species of interest occurring occasionally are *Polygonum viviparum, Equisetum variegatum* and *Orthothecium rufescens*. (Table 2.1)

Cratoneurietum commutati Aich 1933, a related community

The *Cratoneurietum commutati* Aich. 1933 (see above) is sometimes regarded as synonymous with the *Cratoneuretum falcati* Gams 1927 (*e.g.* Oberdorfer 1977). However, it does not contain *Palustriella falcata* or *Arabis soyeri* ssp. *subcoriacea* (Table 2.1).

Zechmeister and Mucina (1994) placed an association *Cratoneuretum commutati* in the *Adiantion* alliance (attributed (on page 400) to Aichinger 1933, but with a minor difference in spelling). This entity is problematic. Apart from the dominance of *Palustriella commutata* in both, there is little in common between the *Cratoneurietum commutati* of Aichinger (1933) and that of Zechmeister and Mucina (1994). The constancy of a number of alpine species in Aichinger's association is at

variance with its placement in the *Adiantion* alliance. The presence of *Eucladium verticillatum* provides a tenuous link, but in both cases it occurs with low frequencies (I). It is perhaps unfortunate that Aichinger applied this name to a specialised alpine community when the species itself is distributed across a broad geographical range of tufaceous springs. Zechmeister and Mucina's application of the name to a substantially different community has rendered it ambiguous and should be rejected.

2.2.5 Association *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977

This association is the lowland to montane equivalent of the alpine *Cratoneuretum falcati* Gams 1927. Its origins lie in Kuhn's *Hypnum commutatum-Cratoneuron filicinum* Community. Oberdorfer's revision is based on 60 relevés; the key species of Kuhn are retained and several more are added (Table 2.1).

The *Cratoneuretum filicino-commutati* is generally dominated by *Palustriella commutata; Cratoneuron filicinum* becomes more frequent in nutrient-enriched sites. Species diversity is low and there are no other constant species. The most frequent accompanying species are *Geranium robertianum* (II), *Eupatorium cannabinum* (II), *Carex flacca* (II), *Bryum pseudotriquetrum* (III), *Eucladium verticillatum* (II) and *Pellia endiviifolia* (II). *Equisetum telmateia* (I), *Hymenostylium recurvirostrum* (I) and *Platyhypnidium riparioides* (I) may also be present (Oberdorfer 1977).

A *Molinia*-rich subassociation forms an intermediate between this association and the *Caricion davallianae* association of rich fens. Here, there is an increase in *Primula farinosa* (V), *Parnassia palustris* (III), *Pinguicula vulgaris* (II), *Crepis paludosa* (II), *Deschampsia cespitosa* (III), *Carex panicea* (IV), *C. lepidocarpa* (IV), *C. hostiana* (IV), *Fissidens adianthoides* (V), *Bryum pseudotriquetrum* (V), *Philonotis calcarea* (IV), *Aneura pinguis* (III) and *Campylium stellatum* (II) (Oberdorfer 1977).

2.2.6 Related communities

The *Cratoneuretum falcati* and the *Cratoneuretum filicino-commutati* are widely recorded associations of petrifying springs, encompassing a broad spectrum of variation in species composition. The following eight syntaxa are somewhat more specialised communities reported from narrower geographical ranges.

Cratoneureto filicinae-Cardaminetum Maas 1959

This lowland spring association described by Maas (1959) has as its character species *Cratoneuron filicinum* and *Equisetum telmateia. Cardamine amara* and *Brachythecium rivulare* (both class character species) reach their optimum here and *Apium nodiflorum* is differential for this association. Two subassociations are distinguished:

- *chrysosplenietosum* Maas 1959 of shady springs with *Chrysosplenium oppositifolium* (and *C. alternifolium*)
- *filipenduletosum* Maas 1959 of lightly shaded springs with *Filipendula ulmaria, Caltha palustris, Equisetum palustre* and *Epilobium hirsutum*.

Cratoneurum filicinum-Conocephalum conicum Community Philippi 1965

This moss-dominated community, and the two that follow, were recorded by Philippi (1965) on shady rock faces irrigated by spring water in Wutachschlucht river valley in the Black Forest. All have small sample sizes, but they give some useful insights at a more detailed level into moss-dominated spring communities. Related to Kuhn's *Hypnum commutatum-Cratoneuron filicinum* Community, the *Cratoneurum filicinum-Conocephalum conicum* Community contains *Cratoneuron filicinum* (V), *Conocephalum conicum* (IV), *Brachythecium rivulare* (III), *Jungermannia atrovirens* (IV) and *Pellia endiviifolia* (II).

Eucladietum verticillati Allorge 1922

This moss-dominated community of steep, irrigated rock faces is usually placed within the *Adiantion* alliance (*e.g.* Dakskobler *et al.* 2014). Philippi recorded it in woodlands in Germany where it contained *Eucladium verticillatum* (V), *Palustriella commutata (V), Aneura pinguis* (IV), *Jungermannia atrovirens* (II), *Bryum pseudotriquetrum* (II) and *Pellia endiviifolia* (II) (Philippi 1965).

Orthothecio-Hymenostylietum curvirostris Community Philippi 1965

In this community of irrigated rocks, *Palustriella commutata* is frequent (V) but usually occurs in small quantities. *Orthothecium rufescens* (V) and *Hymenostylium recurvirostrum* (V) are character species; *Pellia endiviifolia* (V), *Jungermannia atrovirens* (III), *Leiocolea bantriensis* (III) and *Conocophalum conicum* (III) are frequently present (Philippi 1965).

Pellio endiviifoliae-Cratoneuretum commutati Rivola 1982

This lowland association (c. 300m alt.), described from karst regions in former Czechoslovakia, was placed in a new alliance, the *Lycopo-Cratoneurion commutati*, by Hadač (1983). It shares in common with *Cratoneurion commutati* communities several bryophyte species, but also contains vascular plant species which are absent from high altitude spring communities (Table 2.1). Character species of the alliance are *Pellia endiviifolia* and *Eucladium verticillatum*, while those of the association are *Scrophularia umbrosa, Epilobium parviflorum, Lycopus europaeus, Agrostis stolonifera, Palustriella commutata, Bryum pseudotriquetrum*, *Brachythecium rivulare* and *Plagiomnium undulatum* (Hadač 1983).

Zechmeister & Mucina (1994) place this association in the *Adiantion* alliance, within a suballiance, the *Lycopodo-Cratoneurenion commutati*.

Cratoneureto-Saxifragetum aizoidis Nordh. 1943

Coker (1983) provided an important contribution to knowledge of Scandinavian calcareous spring communities in a record from Bøverdal, Norway. Here, the rare moss *Seligeria oelandica* colonises steep, irrigated limestone slabs at an altitude of approximately 1000m. Associated species included *Saxifraga aizoides, S. oppositifolia, Parnassia palustris* and the bryophytes *Hymenostylium recurvirostrum, Blindia acuta, Campylium stellatum* and *Jungermannia atrovirens*.

Cochleario pyrenaicae-Cratoneuretum commutati (Oberd. 1957) Th. Müll. 1961

This community was tentatively described by Oberdorfer (1957) with a single character species, the alpine-subarctic relic *Cochlearia pyrenaica*, and occurring as a community related to the *Caricion davallianae*. Müller (1961) recorded this community on the edges of spring-fed streams in the Alpine foothills of south-west Germany (altitude 540-700m). Oberdorfer (1977) reported 17 samples in total, in which *C. pyrenaica* and *Palustriella commutata* were constant; *Philonotis calcarea, Bryum pseudotriquetrum* and *Campylium stellatum* were frequent and *Tomentypnum nitens* occurred occasionally (Table 2.1).

Equiseto telmatejae-Fraxinetum Oberd. ex Seib. 1987

This woodland association has affinities with the *Carici remotae-Fraxinetum* of flushed, calcareous woodlands, but *Equisetum telmateia* is constant. It develops in a fragmentary form on slopes with trickling water. *Fraxinus excelsior* is usually the dominant tree species, with occasional *Acer pseudoplatanus* (Oberdorfer 1992); in the ground flora, in addition to *Equisetum*

telmateia, *Carex remota* and *Palustriella commutata* are frequent with occasional *Crepis paludosa*.

2.2.7 Synthesis

There is considerable overlap in the species composition of the communities outlined above and their interrelationships are complex. Four main groupings can be distinguished:

- High-altitude alpine springs, of the *Cratoneureto-Arabidetum bellidifoliae* or *Cratoneuretum falcati*, with *Saxifraga aizoides, Arabis soyeri* ssp. *subcoriacea* and *Palustriella falcata.*

- Low to mid-altitude springs, in which *Eucladium verticillatum, Cratoneuron filicinum, Platyhypnidium riparioides, Hymenostylium recurvirostrum, Pellia endiviifolia* and *Conocephalum conicum* become more frequent. These are represented, for example, by Oberdorfer in the *Cratoneuretum filicino-commutati*, by Hadač in the *Pellio endiviifoliae-Cratoneuretum commutati* and by Philippi in a number of more localised communities. These vegetation types have much in common with *Adiantion* communities.

- Woodland springs with *Equisetum telmateia*, contained in the *Equiseto telmatejae-Fraxinetum*.

- Scandinavian springs of the *Cratoneureto-Saxifragion aizoidis* which contain species such as *Thalictrum alpinum, Palustriella decipiens* and *Philonotis fontana*.

Oberdorfer's classification of southern German spring vegetation is in accordance with these groupings (Oberdorfer 1977, 1992). In addition, he draws attention to a *Molinia*-rich community transitional between the *Cratoneuretum filicino-commutati* and peatland communities.

Zechmeister and Mucina's review (1994) is useful in that it moves the *Adiantion* alliance into a closer relationship with the *Cratoneurion*. However, it is unhelpful in elucidating the finer details of the relationships between associations within these alliances.

2.3 British Studies

Although phytosociological methods were not widely adopted in the United Kingdom, two influential Scottish studies did apply the syntaxonomy used in central and northern Europe: McVean and Ratcliffe (1962) in their study of the Scottish Highlands and Birks (1973) working on the Isle of Skye. Prior to these two studies, a number of detailed works on lime-rich springs had been carried out but without the use of phytosociological methods. All of these studies were subsequently incorporated into the National Vegetation Classification (Rodwell 1997, 1998a, 1998b, 1998c, 2000); the communities outlined below belong to NVC spring, flush and mire communities relevant to the present study (see Table 2.4 in Section 2.3.11 for synonomy).

The British studies, not surprisingly, present vegetation of a very different composition to those of Continental Europe. In fact, even amongst the British studies, there is considerable variation in both the physiognomy and species of lime-rich springs in different settings. The most frequently occurring and most ecologically significant species from selected studies are summarised in Table 2.2, with an emphasis on species which are present in Ireland. The descriptions below draw attention to the most important of these species; for clarity, once introduced in the narrative, species are not repeated for every subsequent study unless they are of particular significance in that instance.

The level of detail in these studies is fascinating; there are several close-focus descriptions of the processes at work and sketches of the mosaic patterning of vegetation. In one case (Pigott 1956) the microtopography and juxtapositioning of species is recorded in a number of intricate transects (Fig. 2.3).

2.3.1 Tarn Moor

Holdgate (1955) described the vegetation of springs and flushes on Tarn Moor in Cumbria (altitude 250 – 300m), where large tufaceous mounds (up to 10m in diameter) formed at springheads. The spring water had a pH of 8.0-8.5 (Table 2.3). *Philonotis fontana* formed conspicuous mats at the springheads accompanied by calcicole sedges such as *Carex lepidocarpa, C. panicea, Eleocharis quinqueflora* and *Eriophorum latifolium* and the moss species *Palustriella commutata, P. falcata, Philonotis calcarea* and *Scorpidium scorpioides* (Table 2.2). Forbs included *Pinguicula vulgaris, Parnassia palustris, Pedicularis palustris, Sagina nodosa, Triglochin palustris* and *Tussilago farfara* along with a local spring specialist, *Primula farinosa*, which in Britain is confined to the north of England. It is absent from Ireland.

The adjoining flushes contained tufa granules. Here, plant cover was sparse, consisting mostly of sedges. *Carex lepidocarpa* was abundant in the wettest parts; *Carex dioica*, *C. nigra* and *Schoenus nigricans* are also present. *Chara* sp. was recorded both at the tufaceous mounds and in flushes.

Holdgate refered to the springheads as Tufaceous Mounds and to the sparsely vegetated flushes as Open Surfaces; I will refer to the latter as Open Flushes in subsequent chapters.

Table 2.2: British petrifying spring plant communities recorded prior to the publication of the NVC (*continued overleaf...)*

FORBS CHARACTERISTIC OF PETRIFYING SPRINGS	Tarn Moor Tufaceous Mounds	Tarn Moor Open Flush	Upper Teesdale Gravel Flushes	Upper Teesdale Bryophyte Flushes	Upper Teesdale Turfy Marshes	*C. commutatum - Saxifraga aizoides* Springheads	*Cariceto-Saxifragetum aizoidis* Flush (Lowland Facies)	*Carex panicea - Campylium stellatum* Mire	*Saxifraga aizoides* Banks (*Saxifragetum aizoidis*)	*Cratoneuron-Carex* nodum	*C. commutatum - Saxifraga aizoides* Springheads	*Eriophorum latifolium - C. hostiana* Association	*Carex panicea - Campylium stellatum* Mire	*Saxifraga aizoides* Banks (*Saxifragetum aizoidis*)	*C. nigra - Equisetum palustre* nodum	*Saxifraga aizoides - Tussilago farfara* nodum	*Cratoneuron commutatum* Community	*Cratoneuron filicinum* Community
	Holdg. 1955	Holdg. 1955	Pigott 1956	Pigott 1956	Pigott 1956	McV&R 1962	McV&R 1962	McV&R 1962	McV&R 1962	Eddy 1969	Birks 1973	Birks 1973	Birks 1973	Birks 1973	Huntley 1979	Huntley 1979	Birse 1980	Birse 1980
FORBS																		
Alchemilla glabra				o		I		I	V	II				V	V	V		
Bellis perennis	✓			o-r	r			I	I	III							I	
Caltha palustris (inc. ssp. minor)	✓			r	o	I		I		III								
Cardamine pratensis	✓			o	o	IV		I		V					III		II	✓
Chrysosplenium oppositifolium				r		II				I	✓			I	II	I	II	✓
Cochlearia alpina						I			II	III						III	I	✓
Crepis paludosa								I	II	I	✓			I	III	I		
Epilobium alsinifolium						III		I	II	III						II	IV	
Epilobium anagallidifolium				l.f.				I	I	III					I	I		
Parnassia palustris	✓				o			I	V	I				III		I		
Pedicularis palustris	✓				o		I	II				II			II			
Pinguicula lusitanica							III	I				II						
Pinguicula vulgaris	✓		✓		l.f.	I	V	V	V	I	✓	V	V	V	III	III	I	
Polygonum viviparum						II		II	V	III					IV	V	I	
Sagina nodosa	✓		✓	r				I	I	III								
Saxifraga aizoides			✓		r	V	III	II	V		✓			V		V	III	
Saxifraga hirculus				f						II								
Saxifraga oppositifolia									V					V		II		
Saxifraga stellaris				r		I			II	II					I	I		
Thalictrum alpinum			✓			I		II	III			I		III	III	II	I	
Tofieldia pusilla			✓		o		II	II										
Triglochin palustris	✓	✓	✓		o		II	I		III		III			II			
Tussilago farfara	✓		✓			I			I							IV	I	

d = dominant; a = abundant; f = frequent; o = occasional; r = rare; l = locally; Frequency: I=1-20%, II=21-40%, III=41-60%, IV=61-80%, V=81-100%; ✓ = fewer than five samples or frequency not stated

Table 2.2 (*contd*): British petrifying spring plant communities recorded prior to the publication of the NVC

GRAMINOIDS AND PTERIDOPHYTES CHARACTERISTIC OF PETRIFYING SPRINGS	Tarn Moor Tufaceous Mounds	Tarn Moor Open Flush	Upper Teesdale Gravel Flushes	Upper Teesdale Bryophyte Flushes	Upper Teesdale Turfy Marshes	*C. commutatum* - *Saxifraga aizoides* Springheads	*Cariceto-Saxifragetum aizoidis* Flush (Lowland Facies)	*Carex panicea* - *Campyllium stellatum* Mire	*Saxifraga aizoides* Banks (*Saxifragetum aizoidis*)	*Cratoneuron-Carex* nodum	*C. commutatum* - *Saxifraga aizoides* Springheads	*Eriophorum latifolium* - *C. hostiana* Association	*Carex panicea* - *Campyllium stellatum* Mire	*Saxifraga aizoides* Banks (*Saxifragetum aizoidis*)	*C. nigra* - *Equisetum palustre* nodum	*Saxifraga aizoides* - *Tussilago farfara* nodum	*Cratoneuron commutatum* Community	*Cratoneuron filicinum* Community
	Holdg. 1955	Holdg. 1955	Pigott 1956	Pigott 1956	Pigott 1956	McV&R 1962	McV&R 1962	McV&R 1962	McV&R 1962	Eddy 1969	Birks 1973	Birks 1973	Birks 1973	Birks 1973	Huntley 1979	Huntley 1979	Birse 1980	Birse 1980
GRAMINOIDS																		
Agrostis stolonifera	✓	✓	✓	l.f.		II			I	I					II		II	✓
Carex dioica		✓			f	II	III	II		III		IV	II		III			
Carex flacca	✓	✓			f			II	I	I		IV	III	III	III	II		
Carex hostiana		✓					V	III			✓	V	II		II			
Carex lepidocarpa	✓	✓	✓		a			I	I	I		I			II	II		
Carex nigra	✓	✓		f	a	II	II	III		V		III	III		V			✓
Carex panicea	✓	✓	✓	r	f	II	IV	V		V		V	V	III	IV		I	
Deschampsia cespitosa						IV		I	V	II				V	II	IV	II	
Eleocharis quinqueflora	✓	✓	✓		f		III	IV				V	IV					
Eriophorum angustifolium	✓	✓					IV	IV				I	IV		V			
Eriophorum latifolium	✓				o		IV	II				V						
Festuca rubra				o	l.a.	V		II	V	IV	✓			V	II	IV	V	✓
Juncus articulatus	✓	✓	✓	o	a	I	III	V	I	III		III	V		IV	II		✓
Juncus triglumis			✓			I		I	III	III						I		
Schoenus nigricans		✓					III					V						
PTERIDOPHYTES																		
Equisetum variegatum			✓			I		I										
Selaginella selaginoides			✓	r	o	I	III	V	V	IV	✓	IV	V	V	II	II		

d = dominant; a = abundant; f = frequent; o = occasional; r = rare; l = locally; Frequency: I=1-20%, II=21-40%, III=41-60%, IV=61-80%, V=81-100%; ✓ = fewer than five samples or frequency not stated

Table 2.2 (*contd*): British petrifying spring plant communities recorded prior to the publication of the NVC

BRYOPHYTES CHARACTERISTIC OF PETRIFYING SPRINGS	Tarn Moor Tufaceous Mounds	Tarn Moor Open Flush	Upper Teesdale Gravel Flushes	Upper Teesdale Bryophyte Flushes	Upper Teesdale Turfy Marshes	*C. commutatum* - *Saxifraga aizoides* Springheads	*Cariceto-Saxifragetum aizoidis* Flush (Lowland Facies)	*Carex panicea* - *Campylium stellatum* Mire	*Saxifraga aizoides* Banks (*Saxifragetum aizoidis*)	*Cratoneuron*-*Carex* nodum	*C. commutatum* - *Saxifraga aizoides* Springheads	*Eriophorum latifolium* - *C. hostiana* Association	*Carex panicea* - *Campylium stellatum* Mire	*Saxifraga aizoides* Banks (*Saxifragetum aizoidis*)	*C. nigra* - *Equisetum palustre* nodum	*Saxifraga aizoides* - *Tussilago farfara* nodum	*Cratoneuron commutatum* Community	*Cratoneuron filicinum* Community
	Holdg. 1955	Holdg. 1955	Pigott 1956	Pigott 1956	Pigott 1956	McV&R 1962	McV&R 1962	McV&R 1962	McV&R 1962	Eddy 1969	Birks 1973	Birks 1973	Birks 1973	Birks 1973	Huntley 1979	Huntley 1979	Birse 1980	Birse 1980
BRYOPHYTES																		
Aneura pinguis			✓	r	o	I	III	II	I	IV	✓	III	II	IV	III		I	
Blindia acuta							III			I	✓	IV	III	V		I		
Breutelia chrysocoma							I		II		✓	II	V	I				
Bryum pseudotriquetrum				r	f	II	II	III	IV	V	✓	II	II	IV	IV	V	V	✓
Campylium stellatum			✓		o		V	V	III	II	✓	V	V	I	I	I		
Catoscopium nigritum			✓		r		✓											
Cratoneuron filicinum				f				I	II	IV							II	Char
Ctenidium molluscum	✓				f		III	IV	V	II	✓	II	III	IV				
Fissidens adianthoides				f	f		I	III	III	III		II		II	I			
Gymnostomum aeruginosum										I	✓			II				
Hymenostylium recurvirostrum			✓		r					I	✓			I				
Jungermannia atrovirens					a				I									
Leiocolea bantriensis				f	l.a.				III	II								
Orthothecium rufescens							✓							V		I		
Palustriella commutata	✓			f	o	V	III	IV	III	V	✓	I		III	III	II	V	✓
Palustriella falcata	✓	✓	✓	o	o						✓							
Pellia endiviifolia						I		I	III	I							I	✓
Philonotis calcarea	✓			f	f			II		II	✓							
Preissia quadrata			✓					I	III		✓			IV	I	II		
Scorpidium cossonii			✓	o	a			IV			✓	III	IV					
Scorpidium scorpioides	✓	✓					V	II				V	III					

d = dominant; a = abundant; f = frequent; o = occasional; r = rare; l = locally; Frequency: I=1-20%, II=21-40%, III=41-60%, IV=61-80%, V=81-100%; ✓ = fewer than five samples or frequency not stated

Table 2.2 (*contd*): British petrifying spring plant communities recorded prior to the publication of the NVC

	Tarn Moor Tufaceous Mounds	Tarn Moor Open Flush	Upper Teesdale Gravel Flushes	Upper Teesdale Bryophyte Flushes	Upper Teesdale Turfy Marshes	*C. commutatum - Saxifraga aizoides* Springheads	*Caricetо-Saxifragetum aizoidis* Flush (Lowland Facies)	*Carex panicea - Campyllium stellatum* Mire	*Saxifraga aizoides* Banks (*Saxifragetum aizoidis*)	*Cratoneuron-Carex* nodum	*C. commutatum - Saxifraga aizoides* Springheads	*Eriophorum latifolium - C. hostiana* Association	*Carex panicea - Campyllium stellatum* Mire	*Saxifraga aizoides* Banks (*Saxifragetum aizoidis*)	*C. nigra - Equisetum palustre* nodum	*Saxifraga aizoides - Tussilago farfara* nodum	*Cratoneuron commutatum* Community	*Cratoneuron filicinum* Community
	Holdg. 1955	Holdg. 1955	Pigott 1956	Pigott 1956	Pigott 1956	McV&R 1962	McV&R 1962	McV&R 1962	McV&R 1962	Eddy 1969	Birks 1973	Birks 1973	Birks 1973	Birks 1973	Huntley 1979	Huntley 1979	Birse 1980	Birse 1980
SPECIES OF BROAD ECOLOGICAL RANGE																		
Calliergonella cuspidata				o	f	I		II	IV	II				III	V			✓
Epilobium palustre	✓					I		I		IV					II			✓
Equisetum palustre	✓	✓			l.f.	III		I		III		II	II		V		II	✓
Scorzoneroides autumnalis				o	o			IV		V	✓			I	V			
Linum catharticum			✓		r			II	IV	II					II	II	I	
Molinia caerulea					f-a		V	II				III			I	I		
Prunella vulgaris					f			II	I	III					III	II		
Ranunculus flammula	✓			o	r		I	II		IV		I	II		II			
Succisa pratensis					f-a		III	III	II			IV			IV	I		
NEUTRAL / CALCIFUGE SPECIES																		
Agrostis canina						I		II	I	III								
Carex demissa				I		I	II	IV	III	IV		V	IV		I			
Carex echinata				r			II	III	I	I		III	IV		III			
Carex pulicaris						I	I	IV	III	II	✓	III	III	IV	III	I		
Drosera anglica							V					III						
Drosera rotundifolia							III	I				II	III					
Erica tetralix							IV	III				IV	IV					
Festuca ovina	✓					I	I	III	V	III	✓	III		II	III	III		
Narthecium ossifragum							IV	II				III	II		I			
Philonotis fontana	✓			a		IV		I	III	V					IV	I	III	✓
Trichophorum cespitosum							IV	I										

d = dominant; a = abundant; f = frequent; o = occasional; r = rare; l = locally; Frequency: I=1-20%, II=21-40%, III=41-60%, IV=61-80%, V=81-100%; ✓ = fewer than five samples or frequency not stated

Table 2.3: Water chemistry data and tufa formation notes for published plant community descriptions in Britain. Where individual values are given in the original publication, they are listed below as median, range and sample size.

Community	pH	Calcium mg/l	Tufa
Tufaceous Mounds, Tarn Moor (Holdgate 1955)	8.0 – 8.5	-	Tufa mounds up to 10m diameter
Open Flushes, Tarn Moor (Holdgate 1955)	7.5 - 8.5	-	Tufa granules
Gravel Flushes, Upr Teesdale (Pigott 1956)	-	-	Tufa hummocks 10-20cm
Bryophyte Flushes, Upr Teesdale (Pigott 1956)	6.8	27	-
Cratoneuron commutatum-Saxifraga aizoides nodum (McVean & Ratcliffe 1962)	7.3 7.3 – 7.4 (n=3)	38.87 22.77 – 49.03 (n=3)	'may have incipient tufa formation'
Cariceto-Saxifragetum aizoidis (McVean & Ratcliffe 1962)	6.8 6.8 – 7.2 (n=5)	9.05 5.28 – 13.03 (n=4)	Muds, usually calcareous, sometimes strongly so
Carex rostrata-brown moss nodum (McVean & Ratcliffe 1962)	6.8 6.5 – 6.8 (n=6)	12.56 8.31 – 19.80 (n=5)	-
Cratoneuron-Carex nodum (Eddy *et al.* 1969)	4.9 – 5.1	47 - 106	'a tendency to tufa formation in places'
Cratoneuron commutatum-Saxifraga aizoides nodum (Birks 1973)	7.1 6.8 – 7.4 (n=4)	8.5 7.6 – 9.6 (n=4)	'often incipient tufa-formation'
Eriophorum latifolium-Carex hostiana Association (Birks 1973)	6.8 6.4 – 7.2 (n=6)	8.4 7.0 – 14.8 (n=6)	-
Carex panicea-Campylium stellatum Association (Birks 1973)	6.0 5.6 – 6.2 (n=6)	3.1 2.4 – 3.6 (n=6)	-

2.3.2 Upper Teesdale

Pigott (1956) described from Upper Teesdale in the North Pennines (alt. 405-625m) the related habitats of gravel flushes, bryophyte flushes and turfy marshes (Table 2.2 above).

One gravel flush was tufa-forming, with *Palustriella falcata* at the springhead and an abundance of *Scorpidium cossonii* on flushed gravel. The latter species grew into large cushions on which *Hymenostylium recurvirostrum* became established, and the whole hummock became encrusted with tufa. At maturity, these hummocks were typically 10-20cm high when the moss died locally (probably during droughts); the hummock subsequently broke up, leaving a heap of tufa fragments surrounded by a ring of smaller living moss cushions. The rare moss *Catoscopium nigritum* also occurred on hummocks. Porley and Hodgetts (2005) captured the essence and fragility of the habitat: 'Crunching gingerly through this community where bryophytes are coated with an 'exoskeleton' of calcite feels like walking on eggshells.'

Other species of note in these gravel flushes were *Saxifraga aizoides, Equisetum variegatum, Selaginella selaginoides, Chara vulgaris* and the liverworts *Preissia quadrata* and *Aneura pinguis* (Pigott 1956). The upland species *Thalictrum alpinum* and *Juncus triglumis* were also present, both of which are uncommon in Britain. The former is very rare in Ireland, confined to mountains in the west from Counties Galway to Donegal (Parnell & Curtis 2012) while the latter is absent.

There is no mention of tufa occurring in either the bryophyte flushes or turfy marshes. While calcareous, the bryophyte flushes had a neutral pH (pH 6.8, Table 2.3 above). *Philonotis fontana* was abundant there and frequently occurring species included *P. calcarea, Palustriella commutata, Cratoneuron filicinum, Fissidens adianthoides* and *Oncophorus virens*. The last named species is rare in Britain (Smith 2004) and absent from Ireland. The liverwort *Leiocolea bantriensis* was frequent in this community; though uncommon in Ireland, it is widespread in Britain. Two rare broadleaved herbs were also frequent in these bryophyte flushes; *Epilobium anagallidifolium* occurs in mountain flushes in the north of Britain but is absent from Ireland, while *Saxifraga hirculus* has a very local and declining distribution in Britain (Stace 2010) and is very rare in Ireland, occurring only in bog flushes in Counties Mayo and Antrim and in the Ox Mountains, Co. Sligo (Parnell & Curtis 2012, Muldoon *et al*. 2014).

The turfy marshes carried a rich flora. They were situated below a series of springs and consisted of hummocks scattered over often bare, calcareous, muddy gravel (Fig. 2.3 below). On the hummocks, grasses and sedges predominated, with *Carex lepidocarpa, C. nigra, C. dioica, C. flacca, C. panicea, Festuca rubra* and *Sesleria caerulea* most abundant. These were accompanied by *Pinguicula vulgaris, Saxifraga aizoides* and *Primula farinosa* along with the bryophytes

Palustriella commutata, P. falcata, Philonotis calcarea, Bryum pseudotriquetrum, Campylium stellatum, Fissidens adianthoides and the rare *Catoscopium nigritum*. On the gravel between the hummocks, the bryophytes *Scorpidium cossonii, Jungermannia atrovirens* and *Leiocolea bantriensis* were abundant, along with *Juncus articulatus*, *Eleocharis quinqueflora*, *Carex lepidocarpa* and *C. panicea*. Cattle grazing played an important role in keeping this habitat open and maintaining the presence of rare species.

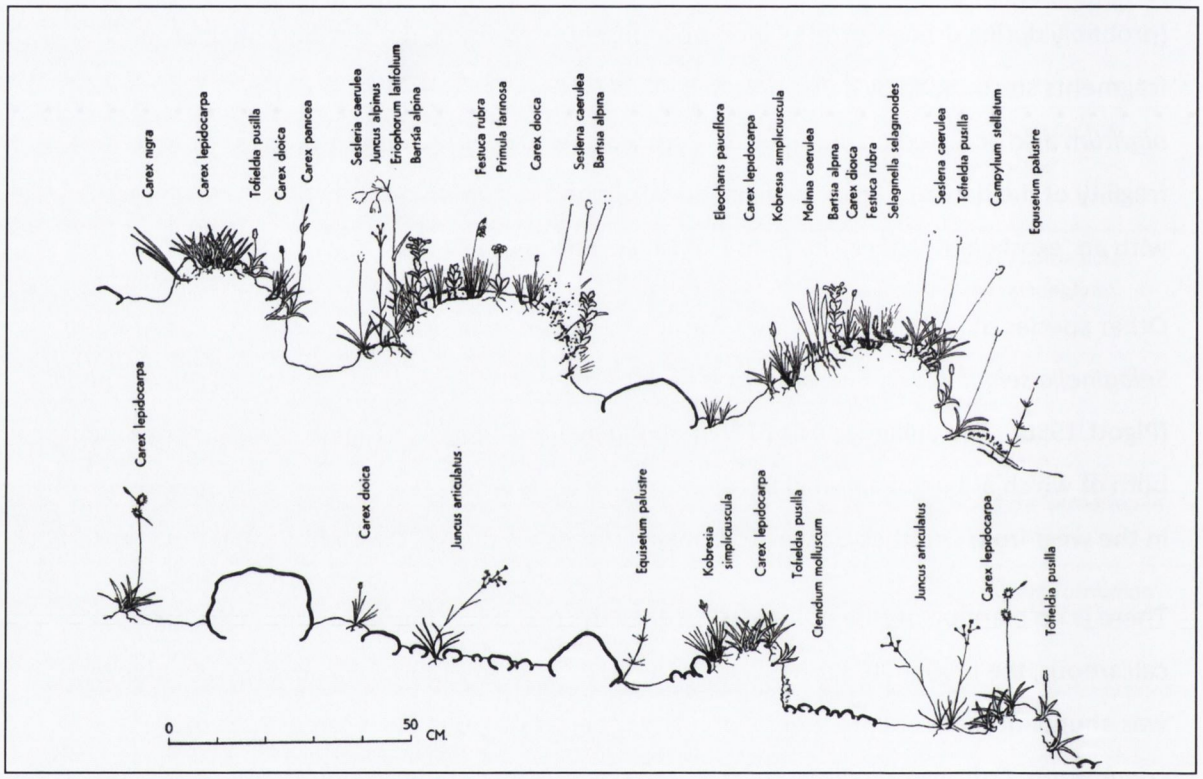


Fig. 2.3: "Transect through the hummock complex at the upper margin of a small calcareous marsh on Widdy Bank Pastures. ... The plants have been drawn as accurately as possible to aid their recognition and to convey the structure of the community. The depth of the humus-stained part of the hummocks is indicated by stippling, but only those boulders visible on the surface are included as the hummocks were damaged as little as possible. The lower diagram is a direct continuation along the same line as the upper." Reproduced from Pigott (1956).

2.3.3 Malham Tarn and District

Proctor (1960) described habitats similar to those of both Tarn Moor and Upper Teesdale (above, Holdgate 1955 and Pigott 1956) from near Malham Tarn; they consisted of permanent seepages or trickles of water on gently sloping ground with hummocks, some of which were substantial and

consisted of tufa. *Palustriella falcata* was the most characteristic bryophyte of the wet ground between the hummocks; also present on the sides and bases of hummocks were *Scorpidium scorpioides, Philonotis calcarea, Fissidens adianthoides, Gymnostomum aeruginosum, Leiocolea bantriensis* and *Aneura pinguis*. He proposed calling these communities "spring fens".

Tufa-forming streams in this district contained plentiful *Palustriella commutata, Cratoneuron filicinum, Bryum pseudotriquetrum, Platyhypnidium riparioides, Pellia endiviifolia* and *Didymodon tophaceus*. Tufa flushes were described as "forming a half-way stage between damp cliffs and calcareous springs" and were "a very characteristic habitat of *Orthothecium rufescens*" (Proctor 1960).

2.3.4 Scottish Highlands

1962 saw the publication of McVean and Ratcliffe's acclaimed 'Plant Communities of the Scottish Highlands' which linked Scottish upland vegetation with the phytosociological descriptions of continental Europe, and in particular with Scandinavian vegetation types. A number of associations (or noda) in this work are of relevance here.

Lime-rich springs and their associated flushes are presented as the *Cratoneuron commutatum – Saxifraga aizoides* nodum and *Cariceto-Saxifragetum aizoidis* flush respectively. These may be flanked by the soligenous mire *Carex panicea- Campylium stellatum* nodum. In addition, the herb and fern meadow category, *Saxifragetum aizoidis*, contains vegetation of irrigated, lime-rich cliffs.

Cratoneuron commutatum-Saxifraga aizoides nodum

This nodum, described here for the first time, occurred at spring heads as a mound or bank of *Palustriella commutata* with sparse growth of grasses, sedges and other herbs. *P. commutata, Festuca rubra* and *Saxifraga aizoides* are constants; *Epilobium alsinifolium* (a montane species locally frequent in the north of Britain, but very rare in Ireland), *Cardamine pratensis, Deschampsia cespitosa* and *Philonotis fontana* were frequently present (Table 2.2 above). The nodum occurred 'only where the spring water is strongly charged with calcium carbonate' (pH 7.3 - 7.4, calcium 22.77 – 49.03 mg/l) and 'incipient tufa formation may take place at the base of the moss cushion'. It had a wide altitudinal range (310-910m). It was stated to be similar to the *Cratoneureto-Saxifragetum aizoidis* of Nordhagen (1943) and Dahl (1956), although the Scandinavian version contained *Palustriella decipiens* and tended to be more montane.

Cariceto-Saxifragetum aizoidis flush vegetation

In the Scottish Highlands study, *Cratoneuron commutatum-Saxifraga aizoides* springs were seldom found to occur without a *Cariceto-Saxifragetum aizoidis* flush (although the latter sometimes occured without the former). Here, as in Tarn Moor and Upper Teesdale, there was sparse plant cover over flushed mud and stones, but the species composition of the Scottish Highland samples was markedly less calcicole in character. In common with the previous studies (Holdgate 1955 and Pigott 1956) are species such as *Pinguicula vulgaris*, *Saxifraga aizoides*, *Carex panicea, C. dioica* and *Eleocharis quinqueflora*, but *Carex demissa* (rather than *C. lepidocarpa*) and *Festuca ovina* (rather than *F. rubra*) are constant in the Scottish montane facies. Even more striking is the prevalence of calcifuge species such as *Narthecium ossifragum, Trichophorum cespitosum, Erica tetralix* and *Drosera anglica* in the Scottish lowland facies. pH (6.8 – 7.2) and calcium content (5.28 – 13.03mg/l) of water were somewhat lower here than in the previous community (Table 2.3 above).

Other noteworthy species in this community were *Pinguicula lusitanica, Carex hostiana, Eriophorum angustifolium, E. latifolium, Schoenus nigricans* and the mosses *Catoscopium nigritum, Orthothecium rufescens*, *Scorpidium scorpioides* and *Campylium stellatum*.

Soligenous mires

The springs and flushes described above were often flanked by the *Carex panicea-Campylium stellatum* nodum, variously placed by the authors within soligenous mires and calcareous flushes (McVean & Ratcliffe 1962, p120 and Map 30). Constant species were *Carex panicea, Campylium stellatum, Selaginella selaginoides, Juncus articulatus* and *Pinguicula vulgaris*. The vegetation was a close-grazed sward with a wide variety of sedge species and with plentiful forbs and grasses. Notable mosses, as well as *Campylium stellatum*, were *Palustriella commutata, Scorpidium cossonii, S. scorpioides, Bryum pseudotriquetrum* and *Fissidens adianthoides*. The altitudinal range was 30 – 730m; water analysis is not reported.

This gave way on more waterlogged calcareous ground to the *Carex rostrata*-brown moss provisional nodum in which *C. rostrata* was dominant in a more open sedge layer with conspicuous brown mosses of the same species as in the previous community. Water composition was comparable to that of the *Cariceto-Saxifragetum aizoidis*; pH (6.5 – 6.8) was slightly lower, but calcium concentrations were somewhat higher (8.31 to 19.80 mg/l, Table 2.3 above).

Saxifraga aizoides Banks

A related community, described under 'Herb and Fern Meadows' rather than wetland communities, was the *Saxifragetum aizoidis* (*Saxifraga aizoides* banks) which occured typically on steep, north-facing slopes (alt. 560 – 790m) with copious seepage of water over lime-rich rock. *Saxifraga aizoides* attained remarkably high cover values (25 – 90%) in this vegetation type, setting it apart from the above categories. Nevertheless, the vegetation is species-rich, with *Alchemilla glabra, Parnassia palustris, Pinguicula vulgaris, Polygonum viviparum, Saxifraga oppositifolium, Deschampsia cespitosa, Festuca rubra, F. ovina* and *Selaginella selaginoides* (Table 2.2 above). The complement of mosses was indicative of somewhat less base-rich conditions than in the communities described above (water composition was not reported); the most frequently occurring species were *Bryum pseudotriquetrum, Ctenidium molluscum* and *Calliergonella cuspidata*.

2.3.5 Isle of Skye

Birks (1973) produced a detailed study of the Isle of Skye in a similar format to the Scottish Highlands survey. As might be expected, it showed considerable overlap in the types of vegetation present and Birks developed these with additional insights and modifications to species lists in the light of new samples.

Cratoneuron commutatum-Saxifraga aizoides nodum springs occurred at lower altitudes on Skye and the list of associated species was expanded to include *Palustriella falcata, Scorpidium cossonii, Gymnostomum aeruginosum, Hymenostylium recurvirostrum* and *Aneura pinguis* (Table 2.2 above). *Pinguicula vulgaris* was more frequent here than in the Scottish Highlands study. Birks also drew attention to the occasional presence of *Crepis paludosa* and *Philonotis calcarea*. Spring water pH ranged to lower values (6.8 – 7.4) and calcium concentrations were markedly less (7.6 – 9.6 mg/l) than in the Scottish Highlands.

Departing from McVean and Ratcliffe's framework, Birks placed the *Saxifragetum aizoidis* within the *Cratoneurion commutati* W. Koch 1928 but commented on its affinities to rock crevice and tall herb communities. *Orthothecium rufescens* was added as a constant species.

Birks' *Eriophorum latifolium-Carex hostiana* Association is the equivalent of McVean and Ratcliffe's low level *Cariceto-Saxifragetum aizoidis* flush vegetation; it commonly occurred below *Cratoneurion commutati* springs on Skye. Once again, it was floristically rich, while low in overall vegetation cover, in consequence of water scouring and grazing. pH values were in the range 6.4

to 7.2 with calcium concentrations of 7.0 to 14.8 mg/l. Species composition was consistent with that of the Scottish Highlands (Table 2.2 above).

The *Carex panicea-Campylium stellatum* Association on Skye occurred also as a closely-grazed, sedge-dominated community where it was very similar to, if somewhat less species-rich than, the Scottish Highland equivalent. pH values were in the range 5.6 to 6.2 and calcium concentrations 2.4 to 3.6 mg/l.

2.3.6 Moor House

Eddy *et al.* (1969) assigned calcareous spring vegetation at Moor House National Nature Reserve in the Northern Pennines to the *Cratoneuron-Carex* nodum in which *Palustriella commutata*, the usual dominant, was occasionally replaced by *Cratoneuron filicinum*. Despite high cover values by the dominant moss species, the nodum was species-rich, containing rare species such as *Epilobium alsinifolium, Polygonum viviparum* and *Saxifraga hirculus* (Table 2.2 above). Tufa formation occurred in places. (This nodum is reported in the NVC as the *Cratoneuron-Carex nigra* nodum, but there is no instance of this version of the name in the original publication. *C. panicea* was marginally more abundant in Eddy *et al.*'s samples than *C. nigra*.)

2.3.7 Western Border Cleuchs

Ferreira (1978) conducted a survey of cleuchs (narrow, rocky glens, wooded presently or in the past) in the south of Scotland. The focus was on recording vegetation types present at various locations rather than elaborating on the composition of individual types. However, he presented three interesting new communities.

He described '*Cratoneuron* drip-zones' as a facies of McVean & Ratcliffe's *Cratoneuron-Saxifraga aizoides* springs – except that, rather than springing, calcium-rich water dripped from above onto cushions of *Palustriella commutata* and the shape of the cushions was dictated by the pattern of the drips. These had the same species composition as *Cratoneuron-Saxifraga aizoides* springs, except that *S. aizoides* was absent – its biogeographical range does not extend into this locality.

He also described *Philonotis calcarea-Cratoneuron* springs, in which *P. calcarea* was dominant. While these did not relate directly to any of McVean and Ratcliffe's categories, they had greatest affinity with a subset of samples within the *Carex panicea-Campylium stellatum* nodum and Ferreira noted that they graded into *Carex*-brown moss mire.

A third community of interest is that of *Gymnostomum* rock clefts, which occurred on wet, calcareous rock and contained *Gymnostomum aeruginosum* and *Eucladium verticillatum*.

2.3.8 Caenlochan

Huntley (1979) conducted a phytosociological survey of Caenlochan National Nature Reserve in the Grampian Mountains in central Scotland. Two vegetation types described in this study are of relevance.

The *Carex nigra-Equisetum palustre* nodum has affinities with the *Carex panicea-Campylium stellatum* nodum of McVean & Ratcliffe (1962) and Birks (1973) (Table 2.2 above). However, *Carex nigra* and *Calliergonella cuspidata* were somewhat more abundant than *Carex panicea* and *Campylium stellatum* respectively in the former nodum; Huntley suggested that this might indicate a lower base status in the *Carex nigra-Equisetum palustre* nodum than in the *Carex panicea-Campylium stellatum* nodum.

The *Saxifraga aizoides-Tussilago farfara* nodum showed affinities to the *Saxifragetum aizoidis* in the habitat it occupied but floristically and in terms of having an open structure, it was closer to the *Cariceto-Saxifragetum aizoidis*. *Tussilago farfara* featured repeatedly in the early *Cratoneurion* descriptions (*e.g.* Koch 1928, Braun-Blanquet 1931, Aichinger 1933, Nordhagen 1937) and occurred in tufa-forming communities at Tarn Moor and Upper Teesdale (Holdgate 1955, Pigott 1956); yet it was largely absent from the communities of the Scottish Highlands and Isle of Skye detailed above.

2.3.9 Lowland and Southern Uplands of Scotland (Birse)

While the Scottish Highlands' vegetation has much in common with that of Scandinavian mountain ranges, the plant communities of the south of Scotland are more closely related to those of the Netherlands and northwest Germany (Birse & Robertson, 1976). Birse (1980) described two additional spring communities from the south of Scotland.

Cratoneuron commutatum Community Birse

Birse's *Cratoneuron commutatum* community occurred in weakly to strongly calcareous springs and flushes on hill slopes; it had high cover by *Palustriella commutata* throughout, accompanied most frequently by *Festuca rubra* and *Bryum pseudotriquetrum*, along with *Epilobium alsinifolium, Saxifraga aizoides, Poa trivialis* and *Philonotis fontana* (Table 2.2 above).

Cratoneuron filicinum Community Birse

Here, *P. commutata* was replaced by *Cratoneuron filicinum*, which was most frequently accompanied by *Festuca rubra, Poa trivialis, Cardamine pratensis, Sagina procumbens, Brachythecium rivulare* and *Philonotis fontana* (Table 2.2 above). This community has affinities with the *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977, occurring on steep hillsides where spring water is intermediate between calcareous and mineral-poor. It is perhaps associated with more nitrogen-rich waters than the *Cratoneuron commutatum* Community (Birse 1980 and Oberdorfer 1977).

Mire and flush communities

Base-rich flushes and mires associated with springs were presented as three sedge-dominated communities with an underlayer of pleurocarpous mosses:

- *Caricetum hostiano-pulicaris* Association (Birse & Robertson 1976) Birse ass. nov.
- *Schoenus nigricans* community
- *Carici dioicae-Eleocharitetum quinqueflorae* Association (Birse & Robertson 1976) Birse ass. nov.

These communities had much in common with each other as well as with those described elsewhere in Scotland and the north of England (above). Species such as *Pinguicula vulgaris, Carex lepidocarpa, C. panicea, Eleocharis quinqueflora, Selaginella selaginoides* and *Saxifraga aizoides* were present in all three, along with the bryophytes *Palustriella commutata* and/or *P. falcata, Campylium stellatum, Scorpidium cossonii* and *Aneura pinguis*. They occurred on level to steeply sloping ground in lowland and upland sites and were often grazed.

A fourth related community occurred in calcareous dune slacks, the *Anagallis tenella-Equisetum variegatum* Association. This mixed sward, with *Parnassia palustris, Pinguicula vulgaris, Selaginella selaginoides, Campylium stellatum, Bryum pseudotriquetrum* and *Scorpidium scorpioides*, was occasionally grazed.

2.3.10 Synthesis of British Studies prior to NVC

These studies present outstanding examples of species-rich, calcareous springs, flushes and mires, with numerous rare species, of high conservation value. There are several underlying ecological gradients, including altitude, angle of repose, water chemistry, water flow rate, as well as the impact of grazing and biogeographical location. The vegetation types outlined above are many-faceted, inviting investigation and understanding from several perspectives.

Clearly, they are closely related, showing considerable overlap in their species composition. Yet they occupy a range of positions relative to the springhead. The complex interrelationships of springs and their associated wetlands presents a challenge, both in the abstract sense of describing vegetation communities and in the more pragmatic matter of choosing and delimiting sampling units on the ground.

The extent to which these communities are tufa-forming is unclear. In six of the above vegetation types, the presence of tufa was recorded (Table 2.3 above). These records range from the massive, consolidated tufa mounds of Tarn Moor (Holdgate 1955) to the possibility of incipient tufa formation in the *Cratoneuron commutatum-Saxifraga aizoides* nodum in the Scottish Highlands and on Skye (McVean & Ratcliffe 1962, Birks 1973). For many communities, there is no reference to the presence of tufa, but in all cases, the emphasis was on recording plant species and the level of detail regarding the accompanying abiotic characteristics is variable. While most of these communities are unlikely to be strongly tufaceous, it is possible that in some tufa was present but not recorded.

In so far as water chemistry data are reported, the highest pH values coincide with strongly tufaceous habitats (Tarn Moor). The Scottish Highlands and Isle of Skye data show ecological gradients in which the highest pH values are recorded at *Cratoneuron commutatum-Saxifraga aizoides* springheads; pH drops slightly in flush vegetation and is lower again in flanking mires.

These works also throw up some anomalies which further confirm the complex nature of the ecology and vegetation patterns. The most strongly tufaceous category, with the highest pH range, Tufaceous Mounds of Tarn Moor (Holdgate 1955), is dominated at the springhead by *Philonotis fontana*, not *P. calcarea*. This is surprising, since *P. calcarea* is strongly calcicolous unlike *P. fontana* (Smith 2004, Hájková *et al.* 2007). However, the ecological tolerance of *P. fontana* in Britain is much broader than that of *P. calcarea* (N. Hodgetts, pers. comm.) so, while the latter species is more characteristic of strongly calcareous habitats, *P. fontana* is not excluded from these situations. (Misidentification could also play a part, especially in older studies,

although in several instances both species were recorded in the same sample indicating that they were being distinguished from each other).

In addition, the microtopography and mosaic composition of the habitat undoubtedly contributes to anomalies. This applies in particular to the recording of calcifuge species such as *Drosera anglica, Narthecium ossifragum* and *Erica tetralix*.

It seems probable that in some of these types we are dealing with vegetation that is on the cusp of what might be considered 'petrifying'. Together, these studies form the backdrop to a number of spring and flush categories in the British National Vegetation Classification.

2.3.11 Britain's National Vegetation Classification

Britain's National Vegetation Classification (Rodwell 1998a,b,c) contains a number of vegetation types which are relevant in the present context, in particular:

- M37 *Cratoneuron commutatum-Festuca rubra* springs
- M38 *Cratoneuron commutatum-Carex nigra* springs
- M10 *Carex dioica-Pinguicula vulgaris* mire
- M11 *Carex demissa-Saxifraga aizoides* mire
- M13 *Schoenus nigricans-Juncus subnodulosus* mire
- U15 *Saxifraga aizoides-Alchemilla glabra* Banks
- W7 *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland

The first two communities, M37 *Cratoneuron commutatum-Festuca rubra* springs and M38 *Cratoneuron commutatum-Carex nigra* springs, correspond to the Habitats Directive category '7220 Petrifying springs with tufa formation (*Cratoneurion*)' (Commission of the European Communities 2013). Both occur, usually over small areas, in springheads and seepages in which *Palustriella* species are dominant. M37 is largely based on McVean and Ratcliffe's *Cratoneuron commutatum-Festuca rubra* spring nodum (Table 2.4 below). It has few other species; the most frequent is *Bryum pseudotriquetrum* (constancy class IV). M38 is more species-rich, with *Carex nigra, C. panicea, C. demissa, Selaginella selaginoides, Polygonum viviparum* and *Philonotis fontana* amongst the species in constancy classes V and IV. The difference between the two communities is principally attributed to grazing and trampling in M38 which limits the dominance of *Palustriella* spp. Thus M38 is usually situated on gently sloping ground, whereas M37 often occurs in steep, inaccessible places.

These communities are both frequently (though not necessarily) tufa forming. Both require sustained irrigation with base-rich, calcareous, oligotrophic water. M37 has a wide altitudinal range, while M38 is more montane in character; the harsh upland climate and cooling spring water favour arctic-alpine species (Rodwell 1998b).

M37 can approach the M38 community and both frequently grade into the more species-rich M10 *Carex dioica-Pinguicula vulgaris* mire, a calcareous, small-sedge community, referable to the *Caricion davallianae* alliance. M10 mires are continuously irrigated by base-rich, oligotrophic water and are often tufa-forming. There is frequently a fine mosaic of microtopographies, often with a hummock-hollow pattern. This community is very variable in its species composition.

Characteristic species, along with the eponymous pair, are *Carex panicea, C. lepidocarpa, C. hostiana, Selaginella selaginoides, Campylium stellatum, Bryum pseudotriquetrum* and *Aneura pinguis*. There are three sub-communities of which the *Briza media-Primula farinosa* sub-community and *Gymnostomum recurvirostrum* sub-community are the most calcicolous; the latter is characterised by a high proportion of bare ground.

At higher altitudes M10 is replaced by M11 *Carex demissa-Saxifraga aizoides* mire. This community is more arctic-alpine in character, and *Saxifraga aizoides* is more frequent here than in M10, along with *Juncus triglumis* and *Thalictrum alpinum*. *Carex lepidocarpa* and *C. hostiana* are less frequent than in M10. M10 bryophyte species are present, though typically less abundant, and the more montane *Blindia acuta* and *Orthothecium rufescens* are added. M11 is characteristically an open community, with strongly scoured runnels irrigated by moderately base-rich water. This community is largely derived from McVean and Ratcliffe's *Cariceto-Saxifragetum aizoidis*. It contains two sub-communities; the *Cratoneuron commutatum-Eleocharis quinqueflora* sub-community is transitional to M10.

Schoenus nigricans is sometimes present in these flush communities, particularly in a variant of M10, but it occurs as part of a mixed sward. In the M13 *Schoenus nigricans-Juncus subnodulosus* mire, it is constant and generally dominant. *J. subnodulosus* is also constant and sometimes predominates.

U15 *Saxifraga aizoides-Alchemilla glabra* banks, synonymous with *Saxifraga aizoides* Banks of McVean and Ratcliffe and Birks, are grouped with montane (rather than mire) communities in the NVC. Consistent with descriptions by the earlier authors, they occur on steep, dripping banks and *S. aizoides* is usually dominant in species-rich vegetation.

W7 *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland contains moderately base-rich flush vegetation. *Filipendula ulmaria* is the most frequent species in the ground flora along with *Lysimachia nemorum*. *Palustriella commutata* occurs in the *Carex remota-Cirsium palustre* sub-community, but with very low frequency (constancy class I), along with *Crepis paludosa* (II), *Carex remota* (III), *Equisetum telmateia* (I) and *Brachythecium rivulare* (III). The authors note that further sampling might lead to the recognition of a separate tufa-forming woodland community with *P. commutata* and *Equisetum telmateia*.

Table 2.4: Synonymy with National Vegetation Classification (Rodwell 1998b,c)

Section	Vegetation type	Source	NVC Code	NVC name
2.3.1	Open Flushes *p.p.*	Holdgate 1955	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.2	Gravel flushes	Pigott 1956	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.2	Turfy marshes	Pigott 1956	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.4	*Carex panicea-Campylium stellatum* nodum *p.p.*	McVean & Ratcliffe 1962	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.5	*Eriophorum latifolium-Carex hostiana* Association	Birks 1973	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.5	*Carex panicea-Campylium stellatum* Association	Birks 1973	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.9	*Caricetum hostiano-pulicaris*	Birse 1980	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.9	*Schoenus nigricans* community	Birse & Robertson 1976	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.9	*Carici dioicae-Eleocharitetum quinqueflorae* Association p.p.	Birse 1980	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.9	*Anagallis tenella-Equisetum variegatum* Association	Birse 1980	M10	*Carex dioica-Pinguicula vulgaris* mire
2.3.4	*Cariceto-Saxifragetum aizoidis*	McVean & Ratcliffe 1962	M11	*Carex demissa-Saxifraga aizoides* mire
2.3.1	Tufaceous Mounds p.p.	Holdgate 1955	M37	*Cratoneuron commutatum-Festuca rubra* spring
2.3.4	*Cratoneuron commutatum-Saxifraga aizoides* nodum	McVean & Ratcliffe 1962	M37	*Cratoneuron commutatum-Festuca rubra* spring
2.3.5	*Cratoneuron commutatum-Saxifraga aizoides* nodum	Birks 1973	M37	*Cratoneuron commutatum-Festuca rubra* spring
2.3.7	*Cratoneuron* springs, *Cratoneuron* drip-zones	Ferreira 1978	M37	*Cratoneuron commutatum-Festuca rubra* spring
2.3.9	*Cratoneuron commutatum* community	Birse 1980	M37	*Cratoneuron commutatum-Festuca rubra* spring
2.3.9	*Cratoneuron filicinum* community	Birse 1980	M37	*Cratoneuron commutatum-Festuca rubra* spring
2.3.2	Bryophyte flushes p.p.	Pigott 1956	M38	*Cratoneuron commutatum-Carex nigra* spring
2.3.4	*Carex panicea-Campylium stellatum* nodum *p.p.*	McVean & Ratcliffe 1962	M38	*Cratoneuron commutatum-Carex nigra* spring
2.3.6	*Cratoneuron-Carex* nodum	Eddy et al. 1969	M38	*Cratoneuron commutatum-Carex nigra* spring
2.3.8	*Carex nigra-Equisetum palustre* nodum p.p.	Huntley 1979	M38	*Cratoneuron commutatum-Carex nigra* spring
2.3.8	*Saxifraga aizoides-Tussilago farfara* nodum p.p.	Huntley 1979	M38	*Cratoneuron commutatum-Carex nigra* spring
2.3.4	*Saxifragetum aizoidis*	McVean & Ratcliffe 1962	U15	*Saxifraga aizoides-Alchemilla glabra* banks
2.3.5	*Saxifragetum aizoidis* Association	Birks 1973	U15	*Saxifraga aizoides-Alchemilla glabra* banks

'Section' refers to numbered sections within this chapter.

2.4 Irish petrifying springs records

2.4.1 Knocknarea Glen, R. Ll. Praeger

Robert Lloyd Praeger (1904) wrote an early and incisive description of an Irish petrifying spring in a note accompanying a photograph taken by Robert Welch (Photo 2.1 below). The photograph is entitled 'Calcareous Tufa in Knocknarea Glen':

"The photograph shows one of the large bosses of calc-sinter or "petrified moss" often met with in limestone districts. The oozing water, highly charged with lime in solution, begins to evaporate on exposure to the air, and, losing carbonic acid, the excess of calcium carbonate is deposited. On this wet spongy material mosses begin to grow, and these, by decomposing the carbonic acid in the water, materially assist the process of precipitation, and their lower leaves and branches become coated with a calcareous crust, the tips of the shoots continuing to grow and to enlarge the boss."

Praeger identified the bryophytes present as *Hypnum commutatum* (syn. *Palustriella commutata*), *Weissia verticillata* (syn. *Eucladium verticillatum*), *Pellia calycina* (syn. *Pellia endiviifolia*) and *P. epiphylla*. (The inclusion of *P. epiphylla* in the list sits uncomfortably with its ecology in the light of subsequent studies; this species is not elsewhere reported from petrifying springs either in Ireland or abroad (Atherton *et al.* 2010).)

2.4.2 International Phytogeographical Excursion 1949

The International Phytogeographical Excursion in 1949 created an opportunity for the phytosociological classification system of continental Europe to be applied to Irish vegetation. Braun Blanquet and Tüxen (1952) provided a record referred to *Cratoneurion commutati* W. Koch 1928 from "a lime-rich, cold spring at the foot of an esker" near Clonaslee, Co. Offaly. It contained *Palustriella commutata, Philonotis* sp., *Leiocolea bantriensis, Bryum pseudotriquetrum, Carex panicea, Cardamine pratensis, Epilobium parviflorum, Apium nodiflorum, Mentha aquatica, Pinguicula vulgaris, Anagallis tenella* and *Jungermannia atrovirens*. (*Philonotis seriata* was included in the list but this is almost certainly not a valid record as the species has never been otherwise recorded from Ireland (Hill *et al.* 2008). In Great Britain it is largely confined to the Scottish Highlands (Smith 2004).)



Photo 2.1: A Robert Welch photograph reproduced from Praeger *et al.* (1904). The caption read: "Calcareous tufa in Knocknarea Glen. A *Weissia verticillata* [syn. *Eucladium verticillatum*] B *Hypnum commutatum* [syn. *Palustriella commutata*] C Marsh Thistle *Cnicus palustris* [syn. *Cirsium palustre*]"

2.4.3 Plant communities of the Burren

Ivimey-Cook and Proctor's comprehensive account of Plant Communities of the Burren (1966) made a substantial contribution to the body of knowledge on petrifying springs in Ireland.

Calcareous Spring Communities

Eight relevés were presented for 'Calcareous Spring Communities' under the heading of *Cratoneurion commutati*. The most frequently occurring species were *Cratoneuron filicinum* and *Pellia endiviifolia* (constant, V); *Agrostis stolonifera*, *Juncus articulatus* and *Carex flacca* were in constancy class IV. Less frequently occurring species included *Palustriella falcata, Philonotis calcarea* and *Bryum pseudotriquetrum*.

One of the lists in this group was recorded in a waterfall rather than a spring, and the authors commented that bryophyte-rich waterfall communities have a close floristic connection with those of springs. They also note that calcareous springs are 'rather surprisingly uncommon' in the Burren, since there are few bands of impermeable rock to bring drainage water to the surface and such springs as there are tend to be seasonal.

Adiantum capillus-veneris stands

Adiantum capillus-veneris was recorded in both seepages and dry rock crevices in the Burren. The authors commented that 'in the humid climate ... *Adiantum* is released from the restriction to moist rock crevices and tufa seepages which give it such a characteristic set of bryophyte associates in the Mediterranean region". Damp habitats are less usual for *Adiantum capillus-veneris* in the Burren, 'but at least they are more reminiscent of its behaviour in southern Europe'. Four of the relevés recorded for this community are indicative of seepages. Along with *A. capillus-veneris*, they contained *Carex lepidocarpa, Pinguicula vulgaris* and the bryophytes *Palustriella commutata, Eucladium verticillatum, Gymnostomum calcareum, Philonotis calcarea, Bryum pseudotriquetrum, Fissidens adianthoides, Preissia quadrata* and *Jungermannia atrovirens*. The rare moss *Orthothecium rufescens* was present in one relevé recorded on Black Head. This is the only station in Ireland for this species outside the north-west where it occurs on the Benbulbin Range and locally in Fermanagh and W. Donegal (Lockhart *et al.* 2012).

2.4.4 White and Doyle's Vegetation of Ireland

White and Doyle (1982) summarised the *Cratoneurion* Koch 1928 in Ireland. They listed *Cratoneuron filicinum, Philonotis calcarea* and *Saxifraga aizoides* as diagnostic species and considered *Equisetum telmateia* a differential species to less calcareous spring vegetation.

They assigned the Clonaslee and Burren samples to *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977 with the diagnostic species *Cratoneuron filicinum* and *Palustriella commutata*.

They referred to the *Saxifragetum aizoidis* McVean and Ratcliffe 1962 a list recorded in north-west Ireland by Birks *et al.* (1969). This consisted of a species-rich assemblage on a north-facing, calcareous schistose cliff (c.100m long) on Slieve League. Here, *Saxifraga aizoides* and *S. oppositifolia* were locally abundant and the rare species *Polygonum viviparum* and *Thalictrum alpinum* were locally frequent. The cliff is described as 'shattered and gully seamed', and the bryophytes suggest a combination of dry surfaces (*Ctenidium molluscum, Neckera crispa* and *Tortella tortuosa*) with localised seepage (*Blindia acuta, Aneura pinguis* and *Preissia quadrata*). *Orthothecium rufescens* was locally frequent. Similar species lists have subsequently been recorded from this locality (Conaghan 1998, Rich 2008).

White and Doyle suggested that the *Cochleario pyrenaicae-Cratoneuretum commutati* (Oberd. 1957) Th. Müller 1961 may occur in wet mountain gullies or cliff faces. They noted the presence of both *Cochlearia pyrenaica* and *Saxifraga hirculus* in a mineral flush at Bellacorrick, Co. Mayo, where *Tomentypnum nitens* was also present (King & Scannell 1960). This vegetation was floristically rich, and while several species (*Cladium mariscus, Triglochin palustris* and *Campylium stellatum*, for example) indicated base-rich flushing, there was also a strong calcifuge component (including *Sphagnum capillifolium, Campylopus atrovirens* and *Eriophorum vaginatum*).

2.4.5 Other relevant studies

Irish small-sedge communities and *Schoenus* fen and flush vegetation were described by Ó Críodáin and Doyle (1994, 1997). There was a strong overlap of species with *Cratoneurion* communities, but these studies did not specifically deal with this type of vegetation and there is no mention of tufa. The most relevant small-sedge community is the *Campylio-Caricetum dioicae* Osvald 1925 em. Dierssen 1982, with *Anagallis tenella* (V), *Carex panicea* (V), *C. demissa* (V), *C. dioica* (II), *C. hostiana* (II), *Eleocharis quinqueflora* (II) and *Campylium stellatum* (III) (Ó Críodáin & Doyle 1994). In the *Schoenetum nigricantis* (Allorge 1922) Koch 1926 fen and flush vegetation, *Schoenus nigricans* and *Molinia caerulea* were constant (V), accompanied by *Carex panicea* (III),

Campylium stellatum (IV) and *Scorpidium scorpioides* (III) (Ó Críodáin & Doyle 1997). Neither *Palustriella* nor *Philonotis* species were reported from the small-sedge communities. In the *Schoenetum nigricantis*, *P. commutata*, *P. falcata* and *Philonotis calcarea* occurred rarely (each in constancy class I).

Bleasdale and Conaghan reported *Cratoneuron commutatum-Festuca rubra* springs on calcareous Lakes Marble bedrock in Connemara (1995). The vegetation was dominated by *Palustriella commutata,* often accompanied by *Anagallis tenella, Festuca rubra, Carex demissa, Bryum pseudotriquetrum* and *Philonotis fontana*. They also recorded *Carex panicea-Campylium stellatum* flushes in which these two named species were constant, along with frequent *Pinguicula vulgaris, Carex pulicaris* and *Aneura pinguis*. Tufa was not reported from either community.

Kelly and Iremonger (1997) and Cross and Kelly (2003) referred calcareous flushed slopes in Knocksink Wood, Co. Wicklow to the *Equiseto telmatejae-Fraxinetum* Oberd. ex Seib. 1987 where *Equisetum telmateia* and *Palustriella commutata* were abundant in runnels below the springhead.

In 'A Guide to Habitats in Ireland', petrifying springs are contained within the category Calcareous Springs FP1 (Fossitt 2000). This category comprises springs kept permanently moist by water that is calcareous and oligotrophic, and which may be tufa-forming. Typical species are given as *Cratoneuron* spp. [which includes *Palustriella* spp.], *Bryum pseudotriquetrum, Festuca rubra, Briza media, Carex dioica, C. pulicaris, C. flacca, C. nigra, Pinguicula vulgaris* and *Equisetum palustre*. *Saxifraga aizoides* is deemed to be characteristic of the habitat.

Petrifying springs of the Slieve Bloom Mountains have been investigated in some detail in the past number of years; they were defined as locations of 'active tufa formation inextricably associated with calcifying bryophyte species' (Heery 2007, Heery & McCorry 2010, Heery *et al*. 2014). The bryophytes *Palustriella commutata, Cratoneuron filicinum, Scorpidium cossonii, Eucladium verticillatum, Didymodon tophaceus, Bryum pseudotriquetrum, Calliergonella cuspidata, Aneura pinguis* and *Pellia endiviifolia* were recorded. Frequently occurring vascular species at these locations included *Geranium robertianum, Agrostis stolonifera, Festuca rubra, Carex flacca, Equisetum telmateia, Hedera helix* and *Fraxinus excelsior* seedlings.

2.4.6 Some comments on Irish studies

Petrifying springs and their associated plant communities have long been recognised in Ireland, if seldom recorded. The Slieve Bloom studies contain the most comprehensive site descriptions to date.

The Slieve League cliff records made by Birks *et al.* (1969) indicate a site of high conservation value that has close links with Scottish communities, particularly the *Saxifragetum aizoidis* (Birks 1973 and McVean and Ratcliffe 1962). There is no reference to tufa formation. Subsequent records of *Saxifraga aizoides* from cliffs on Slieve League (Conaghan 1998, Rich 2008) do not report tufa formation but they do note that the rare montane species *Saxifraga oppositifolia, Oxyria digyna, Polygonum viviparum* and *Saussurea alpina* occur in the same general locality as *S. aizoides*. However, in all cases, these lists are from an area of unspecified extent rather than a single relevé, so that the species do not necessarily co-exist in a single community. None of the lists contains *Palustriella* species. The cliffs are difficult to access and were not visited during the present study.

The uncommon *Cochlearia pyrenaica* ssp. *alpina* occurs in upland areas in the north-west of Ireland (BSBI website, accessed 13th Nov. 2014, Parnell & Curtis 2012). King and Scannell's (1960) mineral flush at Bellacorrick was exceptionally species rich and ecologically interesting but not strongly indicative of a petrifying spring community. This area has been drastically modified by drainage and peat extraction in the intervening period. A search was made of the area as part of the present study and some ecologically interesting calcareous flushes were located, but *Cochlearia pyrenaica* ssp. *alpina* was not found (nor any other *Cochlearia*).

2.5 Habitats Directive

A short circumscription of petrifying springs in the context of the Habitats Directive is provided in the Interpretation Manual (Commission of the European Communities 2013).

Characteristic species (relevant in the context of Ireland) listed in the Interpretation Manual are: *Pinguicula vulgaris, Saxifraga aizoides, Catoscopium nigritum, Cratoneuron commutatum* (syn. *Palustriella commutata*), *C. commutatum* var. *falcatum* (syn. *Palustriella falcata*), *C. filicinum, Eucladium verticillatum, Gymnostomum recurvirostrum* (syn. *Hymenostylium recurvirostrum*), *Philonotis calcarea, Scorpidium cossonii* and *Bryum pseudotriquetrum*.

Other species listed in the Manual for petrifying springs are species which (i) don't occur in Ireland, (ii) typically occur in slightly different ecological conditions and are unlikely to be present in petrifying springs or (iii) are rare and their occurrence in petrifying springs has not yet been recorded in Ireland:

- *Arabis soyeri, Cratoneuron decipiens, Epilobium davuricum* and *Juncus triglumis* are absent from Ireland.
- *Drepanocladus vernicosus* (syn. *Hamatocaulis vernicosus*) is rare in Ireland and typically occurs in flushes and fens with pH <7.0 (Campbell 2013).
- *Scorpidium revolvens* typically occurs in flushes with lower pH values than those of petrifying springs. This species was formerly known as *Drepanocladus revolvens*, within which *D. revolvens* var. *intermedius* (syn. *Scorpidium cossonii*) was included and there is confusion over the distribution of the two species. *S. cossonii* is characteristic of more base rich habitats than *S. revolvens* (Hedenäs 1989, Blockeel 2000, Smith 2004).
- *Carex appropinquata* and *Cochlearia pyrenaica* are rare in Ireland and are not characteristic or indicative of petrifying springs.

The Corine Biotopes Manual (on which the Habitats Directive Interpretation Manual was based, Evans 2006) also includes *Equisetum telmateia* and *E. variegatum* in the habitat type 54.12 Hard Water Springs with *Cratoneurion commutati* vegetation. In the sub-category 54.121 Tufa Cones, it includes the species *Carex lepidocarpa* and *Sesleria caerulea* (Commission of the European Communities 1991).

2.6 Some recent local studies

Local habitat studies carried out elsewhere include a description of the moss communities (including those of petrifying springs) in Lower Saxony, Germany (Drehwald & Preising 1991), an inventory of petrifying springs in Languedoc (Klesczewski *et al.* 2004), the implementation of conservation measures for petrifying springs in Bavaria (Jokić 2007) and, most recently, a botanical and hydrogeological investigation of petrifying springs in Wales (Graham & Farr 2014).

3. Plant communities of petrifying springs

This chapter contains the results of relevé data collected islandwide during the present project, between April 2011 and September 2013. Data collection and analysis methods are reported in Section 3.1. Eight plant communities of Irish petrifying springs, derived from analysis of field data, are described in turn in Section 3.2, in terms of their floristic composition, rare and ecologically significant species, abiotic characteristics and geographical range. Some typical samples are briefly described for each community and there is a short note on the syntaxonomic affinities of each community (expanded upon in Chapter 4). Ordinations of relevés are presented in Section 3.3 and relationships between the communities are discussed.

3.1 Methods

3.1.1 Field Methods

Sites were selected for survey as per Sections 1.1 and 1.4. Pilot field surveys commenced in the autumn of 2010 to determine the range of variation within the habitat and to devise appropriate methods for collecting data in the field. Approximately 65 sites were visited; these had a wide geographical range – spread over 14 counties – and occurred in different landscape settings. Based on this, a relevé record sheet was designed (Appendix VII). Fieldwork took place during three field seasons, in 2011, 2012 and 2013.

A quadrat size of 2m x 2m was chosen, the maximum suggested size for sampling herbaceous vegetation (Kent 2012). This large size was deemed necessary to encompass the range of microhabitats which frequently occur in petrifying springs. Since the extent of the habitat is often quite small, it was sometimes necessary to modify the quadrat shape to 1m x 4m or to an irregular $4m^2$ area. In a small number of cases (2%), the area impacted by the spring was less than $4m^2$ and quadrat size was reduced accordingly. At larger sites - where there was more than one spring and/or vegetation type, or where diffuse seepage extended over large areas – two or more relevés were recorded to represent the range of variation present within the relevant habitats. Quadrats were placed within spring-influenced vegetation so as to avoid, in so far as possible, areas that were not irrigated by spring water (*e.g.* Photos 3.8, 3.12, 3.13, 3.15 and 3.32), although this was not always achievable due to the mosaic structure of the habitat (*e.g.* Photo 3.34).

Tufa types present were classified according to Pentecost (1995) (see Chapter 1) and the area occupied by each type was recorded as a percentage of the surface area. 'Non-tufa' indicates the

proportion of the quadrat area where tufa was lacking. Paludal tufa is difficult to measure since it can form in patches at different densities. For each relevé containing paludal tufa, the category which best described the strength of formation was selected from the following list and the extent of that category was estimated as a percentage of surface area:

- Paludal strength 1 = weakly formed, discontinuous, inconspicuous tufa; trace on soil or at base of plants
- Paludal strength 2 = intermediate
- Paludal strength 3 = strongly formed tufa, often crunchy underfoot, coating the ground with a conspicuous white layer, often with detached chunks of consolidated tufa.

Water features within relevés were characterised according to whether there was flowing or trickling surface water, impounded surface water ('pools'), dripping water (irrigating vegetation within the quadrat), damp surfaces or dry areas not impacted by the spring. The percentage area occupied by each type was estimated by eye. Repeated visits to certain sites (*e.g.* Glenasmole, Slieve Blooms, Louisa Bridge, coast near Skerries) indicated that, for the most part, these water features are remarkably constant throughout the year.

Cover by each species was estimated as a percentage of the sample area. Total cover by forbs, graminoids, bryophytes, woody species and pteridophytes was recorded, along with total living vegetation, leaf litter (including standing dead vegetation), bare tufa, bare stone and bare soil. 'Graminoids' included grasses, sedges and rushes, but not other monocotyledons.

'Bare tufa' refers to surfaces without vascular plants, bryophytes or charophytes. Algae are typically present on 'bare tufa' but often as thin films which are more or less invisible to the naked eye. Since there is a continuous gradation from conspicuous forms to inconspicuous microscopic forms, algal cover was not quantified. Where clearly visible, the presence of algae was noted (for example, as green filamentous algae) but the tufa surface was nevertheless quantified as 'bare tufa'.

Charophytes were the only algal group that was included in systematic sampling. Other algae and cyanobacteria were collected from a small number of springs, particularly if they were conspicuous or abundant.

Most site names were taken from Discovery Series maps (Ordnance Survey Ireland); in a small number of cases, names were taken from historic Ordnance Survey maps (www.osi.ie) or local names were used. Grid references and altitude were recorded with a handheld Garmin Etrex GPS unit.

3.1.2 Data Analysis

Data were analysed using PC-ORD Version 5.33 (McCune & Mefford, 2006) and R (Version 3.0.3).

Cluster Analysis and Indicator Species Analysis

Relevés were assigned to groups using fuzzy clustering (Borcard *et al.* 2011). Rather than allocating samples to a single group, each sample is given a set of membership coefficients indicating the strength of relationship to some or all of the clusters in the data set. This results in a nuanced approach which is more realistic in ecological situations where there are few sharp boundaries between groups of samples.

Fuzzy clustering was carried out using the 'fanny' function in the R package Cluster (Kaufman & Rousseeuw 2005). This seeks to minimise the formula:

$$\sum_{v=1}^{k} \frac{\sum_{i,\, j=1}^{n} u_{iv}^2 u_{jv}^2 \, d(i,\, j)}{2\sum_{j=1}^{n} u_{jv}^2}$$

where u_{iv} is the membership of object i in cluster v and d is the distance between pairs of objects i and j.

Analysis was carried out on square-root transformed relevé data using the Sørensen (Bray-Curtis) coefficient to create the distance matrix. The membership exponent was set at 1.1. (Setting the membership exponent at 1.0 results in 'hard clustering', where samples are assigned to one cluster only. Raising the value increases the 'fuzziness' of the clusters. With the present data set, increasing the membership exponent to 1.2 approached complete fuzziness, which yields no information; the value 1.1 was deduced to be most appropriate.)

A silhouette plot of samples is one of the outputs of fuzzy clustering. This illustrates how well each sample fits the cluster in which it has the highest membership coefficient, and shows how cohesive the cluster is. High positive silhouette values indicate objects that are "well-clustered"; negative silhouette values show samples that fit poorly in the cluster (Kaufman & Rousseeuw 1990).

The number of clusters (k) must be specified in advance. Beginning with k=4, separate analyses were run for each value of k up to 18. For each set of results, Indicator Species Analysis (ISA) was run, using PC-ORD Version 5.33 (McCune & Mefford 2006). This method combines information on the abundance of a species in a particular group with its faithfulness to that group, to produce an Indicator Value for each species in each group. A perfect indicator of a group is present in all

samples of that group and absent from all other groups. Indicator Values are expressed as a percentage of perfect indication. They are tested for statistical significance using a randomisation (Monte Carlo) technique.

ISA provides a means of choosing the optimal number of clusters (Dufrene & Legendre 1997); it assesses how well species are separated between groups. The cluster arrangement which maximises species similarities within groups and differences between groups will have a high number of significant indicator species. It will also have a low mean p-value of statistically significant indicator species. Either the highest number of significant indicators or the lowest p-value, or both, can be used as the basis for selecting the most informative value of k (McCune & Grace 2002).

In the preliminary stages of statistical analysis, hierarchical agglomerative clustering (McCune & Mefford, 2006) was carried out. This yielded groups with fewer significant species than fuzzy clustering and was therefore not pursued further.

Multi-level Pattern Analysis

In addition to ISA, Multi-level Pattern Analysis of species was carried out using the 'multipatt' function in the R package Indicspecies (Version 1.7.1). This is similar to ISA, but analyses the association between species patterns and combinations of groups of sites, rather than just single groups. Species have different niche breadths and indicator species analysis of individual groups may fail to reveal the association between species and groups; considering all possible combinations of groups overcomes this (De Cáceres *et al.* 2010).

In the present analysis, all possible combinations of groups were tested, so that species could be assigned to any number of groups from one to seven. (The maximum number of groups to which a species can be assigned can be selected in advance; if set to one, the analysis would be the same as ISA.)

Non-metric Multidimensional Scaling (NMS)

Ordinations of relevé data were produced by Non-metric Multidimensional Scaling (NMS) in PC-ORD. Ordination techniques allow complex data sets to be visualised by displaying the strongest structure – they simplify factors affecting the data into a reduced number of dimensions that explain the majority of the variation. The distance of objects in ordination space is a function of how similar they are, so that objects that are close together are more similar than those that are far apart. NMS is highly suited to ecological data which are non-normal and sparsely populated (McCune & Grace, 2002). It is an iterative ordination technique which overcomes some of the

problems associated with earlier ordination methods such as PCA and CCA. Prior to conducting NMS, species occurring in less than four samples were removed from the data set and a square-root transformation was performed on relevé data to reduce the skewness of species distributions and to reduce overall variance. The ordinations were produced in 'slow and thorough autopilot' mode using the distance measure Sørensen (Bray-Curtis). In the preliminary run, random starting configurations were used with 250 runs for real data over 6 dimensions. 250 randomised runs were used for a Monte Carlo test to determine the probability of the final stress value being obtained by chance.

Environmental variables can be overlaid on ordinations to show their relationships to relevés. PC-ORD uses Pearson correlation coefficients for these overlays. They provide a useful means of visualising relationships but, for non-parametric data, Spearman rank correlation coefficients are more statistically appropriate. These were computed separately using R.

Multi-response Permutation Procedures (MRPP)

Multi-response Permutation Procedure (MRPP) is a non-parametric method for testing for differences between groups. 10 abiotic characteristics (cascade tufa, paludal tufa, stream crust tufa, non-tufa, flowing/trickling water, pools, slope, canopy cover, leaf litter and bare stone) were tested using PC-ORD Version 5.33. Variables were relativised (by column total) before analysis and the distance measure used was the Sørensen coefficient (in keeping with NMS analysis, McCune & Grace 2002). MRPP produces a statistic A that describes within-group homogeneity compared to the random expectation. $A = 1$ when all samples within groups are identical, $A = 0$ when heterogeneity within groups equals expectation by chance and $A < 0$ when within group heterogeneity is greater than that expected by chance (McCune & Grace 2002).

3.1.3 Some notes on the text

Frequency

The frequency with which species occur in groups of samples is denoted by Roman numerals: I = up to 20%, II = 21% to 40%, III = 41% to 60%, IV = 61% to 80% and V = 81% to 100%. 'Constant' species are those in constancy classes IV and V. In general, common or frequent species are those in class III, while species in class II are referred to as occasional and in class I as scarce (Rodwell 1998), although, to maintain the flow of the text, I have not adhered strictly to using these terms in this sense.

Ground cover

Ground cover values for species and variables (such as tufa formation type) are estimated as a percentage of the area sampled. For individual relevés, they are an estimate of the proportion of the ground covered by the species or variable, made by eye at the time of recording the relevé. For plant communities, they are the mean of all samples in that group.

Probability Values

Asterisks denote p-values as follows: *** p-value <0.001; ** p-value <0.01; * p-value <0.05.

Synoptic tables

Synoptic tables for each community contain statistically significant Indicator Species in constancy classes II and higher. They also show the most frequently occurring non-indicator companion species (constancy class III or higher); selected species with lower frequencies are sometimes included if referred to in the text (see Appendix III for full synoptic table). Species which are not statistically significantly linked to any group are denoted by 'ns' for the group in which they have their highest Indicator Value.

3.2 Results of Fuzzy Cluster Analysis

In total, 186 relevés were recorded from 18 counties (Map 3.0). Indicator Species Analysis of fuzzy cluster outputs led to the selection of eight groups as the optimal arrangement of relevés into clusters. An eight group solution yielded 108 statistically significant indicator species, with a mean p-value of 0.0092 (Fig. 3.1 and 3.2). Alternative options were to select k=5 which has one extra significant species but a slightly higher mean p-value (0.0099) or k=16 with 108 significant species and again a slightly higher mean p-value (0.0095). The eight-group arrangement was found to have an ecological integrity to the groups. Moreover, it is intermediate between the coarser five-group option and the small sample sizes entailed by the sixteen-group option.

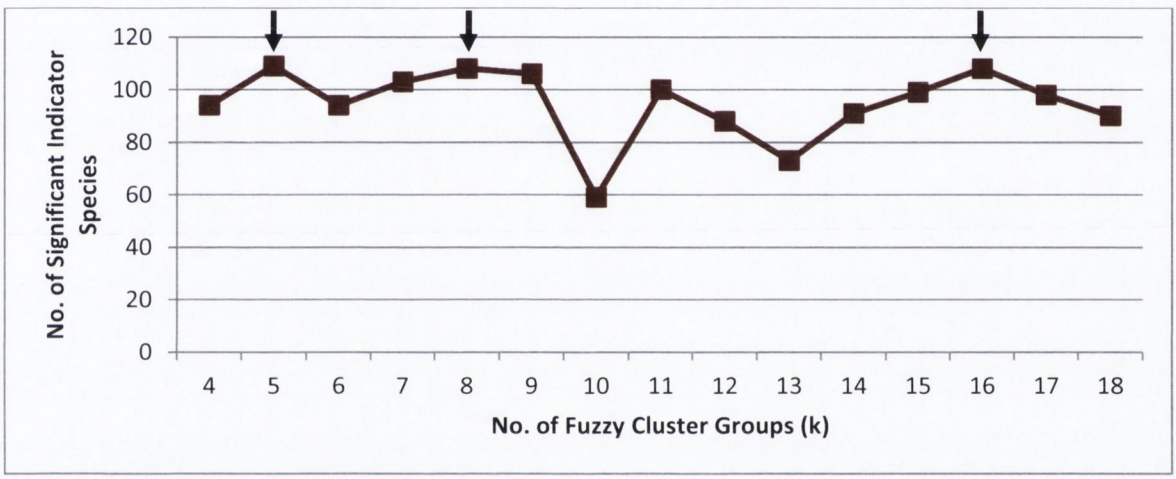


Fig. 3.1: Number of statistically significant indicator species (from Indicator Species Analysis) in fuzzy cluster groups. Highest values, indicated by arrows, were for k=5, k=8 and k=16.

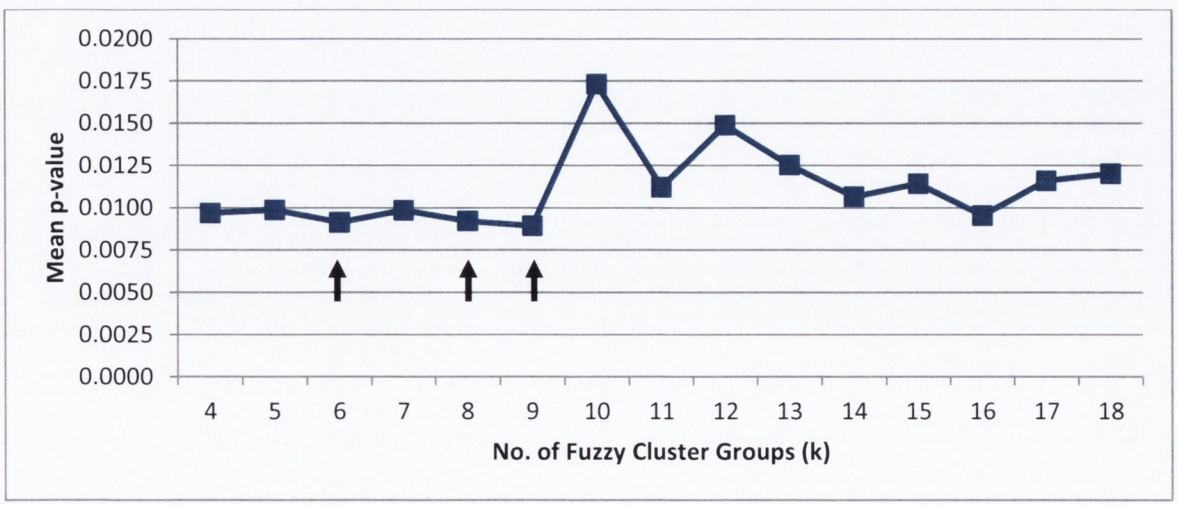
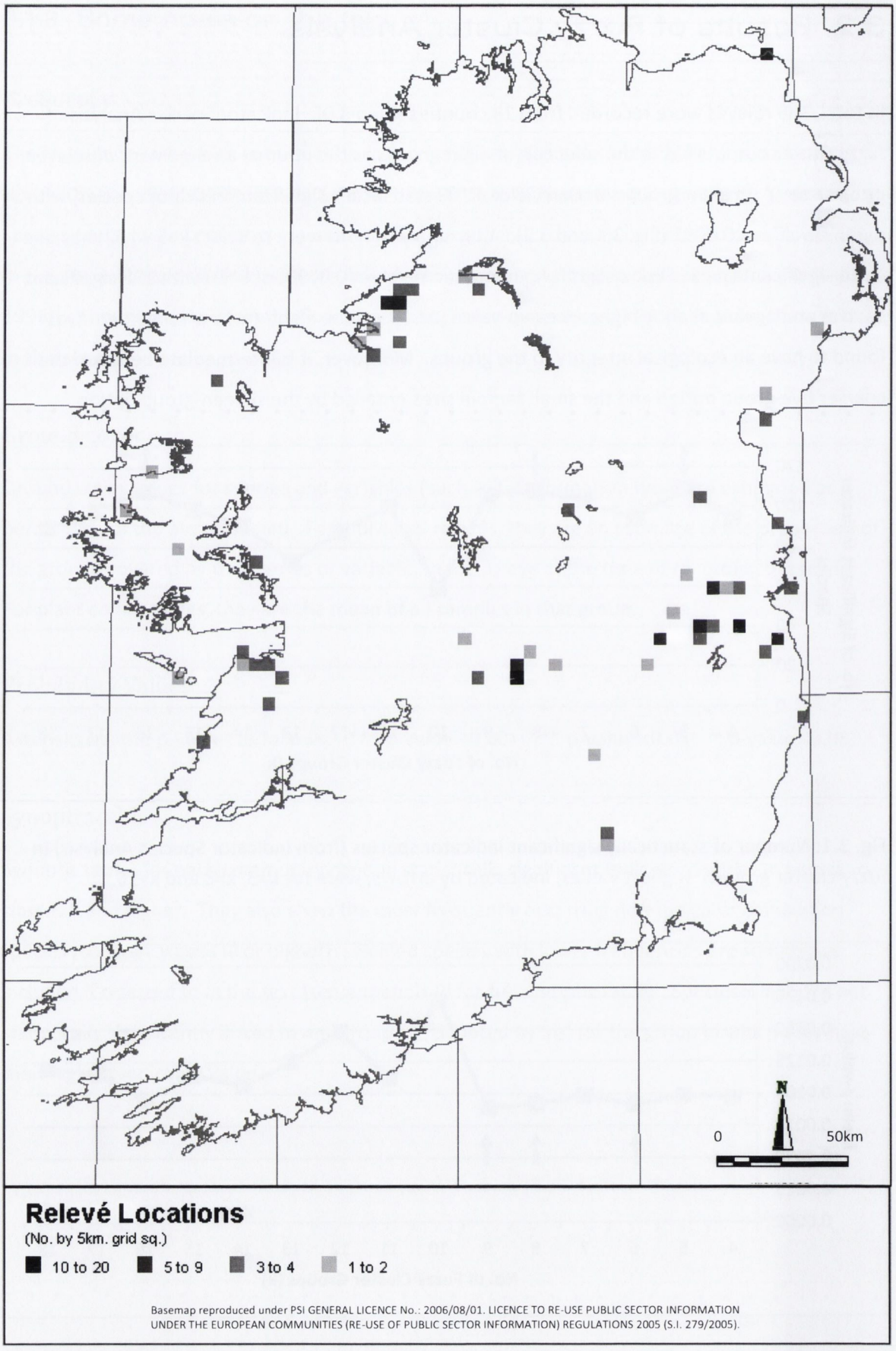


Fig. 3.2: Mean p-value for statistically significant species (from Indicator Species Analysis) in fuzzy cluster groups. Lowest values, indicated by arrows, were for k=6, k=8 and k=9.



Map 3.0: Locations of all relevés (n=186)

The eight-group arrangement produces groups which contain from 13 samples (Group 8) to 30 samples (Group 6). The silhouette plot (Fig. 3.3) shows how well objects are clustered within the groups. The strongest groups are Groups 1, 5, 8 and 2, with mean silhouette widths of 0.20, 0.17, 0.17 and 0.16 respectively. Group 3 is the least cohesive group, having the lowest mean silhouette width (-0.01). Group 4 is also a relatively weak group (mean silhouette width 0.04).

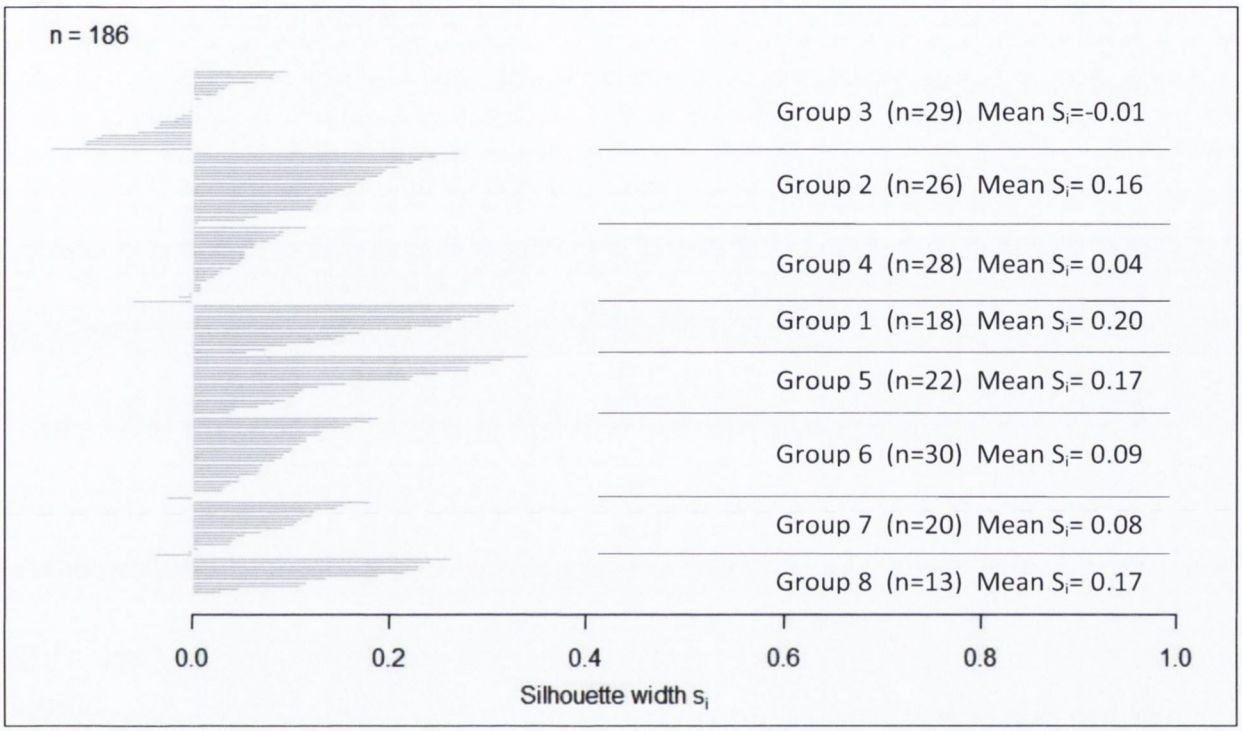


Fig. 3.3: Silhouette plot of fuzzy cluster groups for an eight-group solution. High positive values indicate well-clustered samples.

MRPP shows a very highly statistically significant difference between Groups (A = 0.2347, $p<0.001$) based on abiotic characteristics. Pairwise comparisons show that most Groups (79%) are very highly statistically significantly different to the others (Dunn- Šidák corrected p-value <0.001, Table 3.0).

Table 3.0: MRPP results for differences between pairs of Groups using 10 abiotic variables. Dunn-Šidák correction for multiple comparisons applied to p-values. Abiotic variables tested: cascade tufa, paludal tufa, stream crust tufa, non-tufa, flowing/trickling water, pools, slope, canopy cover, leaf litter and bare stone.

	G1	G2	G3	G4	G5	G6	G7	G8
Group 1	-	**	***	***	***	***	***	***
Group 2		-	*	***	***	***	***	***
Group 3			-	***	***	***	***	***
Group 4				-	***	***	ns	***
Group 5					-	ns	***	***
Group 6						-	**	***
Group 7							-	*

3.2.0 Overview of Plant Communities

The eight plant communities of Irish petrifying springs (*i.e.* fuzzy cluster groups) are as follows:

No.	Name	Section
Group 1	*Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades	3.2.1
Group 2	*Palustriella commutata-Geranium robertianum* Springheads	3.2.2
Group 3	*Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes	3.2.3
Group 4	*Palustriella commutata-Agrostis stolonifera* Springheads	3.2.4
Group 5	*Schoenus* Springs	3.2.5
Group 6	*Carex lepidocarpa* Small Sedge Springs	3.2.6
Group 7	*Palustriella falcata-Carex panicea* Springs	3.2.7
Group 8	*Saxifraga aizoides-Seligeria oelandica* Springs	3.2.8

A description of the floristic composition and ecological characteristics of each group follows. Data relevant to the eight communities can be found in tables and figures (located at the end of the plant community descriptions) and in the appendices:

Ref.	Contents	Section
Table 3.9	General attributes of plant communities	3.2.9
Table 3.10	Top 20 species by % cover	3.2.9
Fig. 3.4	Ground cover by plant groups	3.2.9
Fig. 3.5	Relative abundance of four leading bryophytes	3.2.9
Fig. 3.6	Tufa formation types	3.2.9
Fig. 3.7	Surface composition	3.2.9
Fig. 3.8	Water characteristics	3.2.9
Fig. 3.9	Boxplots of selected attributes	3.2.9
App. I	List of sites	
App. II	Plant communities: summary details of samples in each fuzzy cluster	
App. III	Synoptic table: all Groups with ISA and Multi-level Pattern Analysis	
App. IV	Data for variables in Figs 3.4, 3.6, 3.7 and 3.8	

Photographs are located at the end of the chapter.

3.2.1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades

Group 1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades contain massive, steep tufa cascades and exemplify extreme tufa-forming habitats in which few species can survive. The calcicole moss *Eucladium verticillatum* is constant, often accompanied by *Didymodon tophaceus*.

This is a cohesive group, with the highest mean silhouette width (0.20, Fig. 3.3). There are 18 samples, most of which have membership coefficients of at least 95% (see App. II).

3.2.1a Floristics

Eucladium verticillatum (V) and *Didymodon tophaceus* (III) are highly significant indicators (ISA ***, Table 3.1). *E. verticillatum* is the most abundant species in Group 1 occupying, on average, 25% of the surface area. It typically occurs on vertical tufa surfaces where it is often somewhat shaded by aspect, microtopography or overhanging vegetation (Photo 3.1; Pentecost & Zhaohui 2006). *D. tophaceus* frequently accompanies *E. verticillatum*, but it seldom occupies large areas (mean cover 3%). *Pellia endiviifolia* (IV) is also significant to the group and is sometimes abundant (mean cover 11%).

Bryophytes dominate the vegetation here more than in any other group (Fig. 3.4); vascular plants do not appear in the top five most abundant species (Table 3.10). *Palustriella commutata* is present in most samples (78%), and is almost as abundant as *E. verticillatum*, with mean cover of 20% (Fig. 3.5). *Conocephalum conicum* agg. and *Palustriella falcata* are also present in small quantities.

The most frequently occurring vascular plants are *Agrostis stolonifera* (IV) and *Festuca rubra* (III); these have low cover values (mean cover 1% each) and overall graminoid cover is lowest in this group (2% cover, Fig. 3.4).

Samples are divided almost equally between coastal spray zone cliffs and inland (mostly wooded) locations (App. II). Accordingly, canopy cover is variable, absent from coastal cliffs but often dense (65% to 95%) at inland sites. At coastal sites, *Plantago maritima*, *Cochlearia officinalis*, *Samolus valerandi*, *Armeria maritima*, *Carex distans* and *C. extensa* occur in this group (constancy classes II and I). Woodland samples contain *Hedera helix* and *Geranium robertianum* (both constancy class II).

In spite of the mixture of dominant bryophytes (Fig. 3.5), this group has the lowest species diversity with a mean of only 9 species per relevé on average (Fig. 3.9). 22% of relevés contain four or fewer species each.

Table 3.1: Summary of statistically significant Indicator Species and other frequently occurring species in *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades (Group 1).

ISA	Species	Frequency	Mean % Cover	Minimum % Cover	Maximum % Cover
***	*Eucladium verticillatum*	V	25	2	70
***	*Didymodon tophaceus*	III	3	0.1	20
**	***Pellia endiviifolia***	**IV**	**11**	**1**	**70**
ns	***Plantago maritima***	**II**	**1**	**0.5**	**10**
ns	*Conocephalum conicum* agg.	I	1	3	5
	Palustriella commutata	IV	20	2	60
	Agrostis stolonifera	IV	1	0.1	3
	Festuca rubra	III	1	0.1	3

3.2.1b Rare Species

Chroothece sp.

I found the unicellular red alga, *Chroothece*, at two coastal locations in this group[1]: near Skerries, Co. Dublin and at Spanish Point, Co. Clare. I also found it at a site close to the coast in Co. Antrim (QL210 Marconi's Cottage, Group 4). It forms orange, mucilaginous patches on damp, vertical tufa faces. (Photos 3.01 – 3.04).

This genus is new to Ireland. It has recently been collected from a number of tufaceous seepages in Britain, including both coastal and inland sites (Pentecost *et al.* 2013). Prior to this, there were only two records for Great Britain and Ireland: West Yorkshire 1901 and Port Erin, Isle of Man 1957 (John *et al.* 2011). Taxonomy at species level is unresolved. Species separated on the basis of cell size have been shown to overlap and Pentecost *et al.* concluded that, based on cell dimensions, only one taxon, *C. richteriana*, could be recognised.

[1] It is present within QL051 Spanish Point, but lies just outside QL154 near Skerries

3.2.1c Environmental Variables

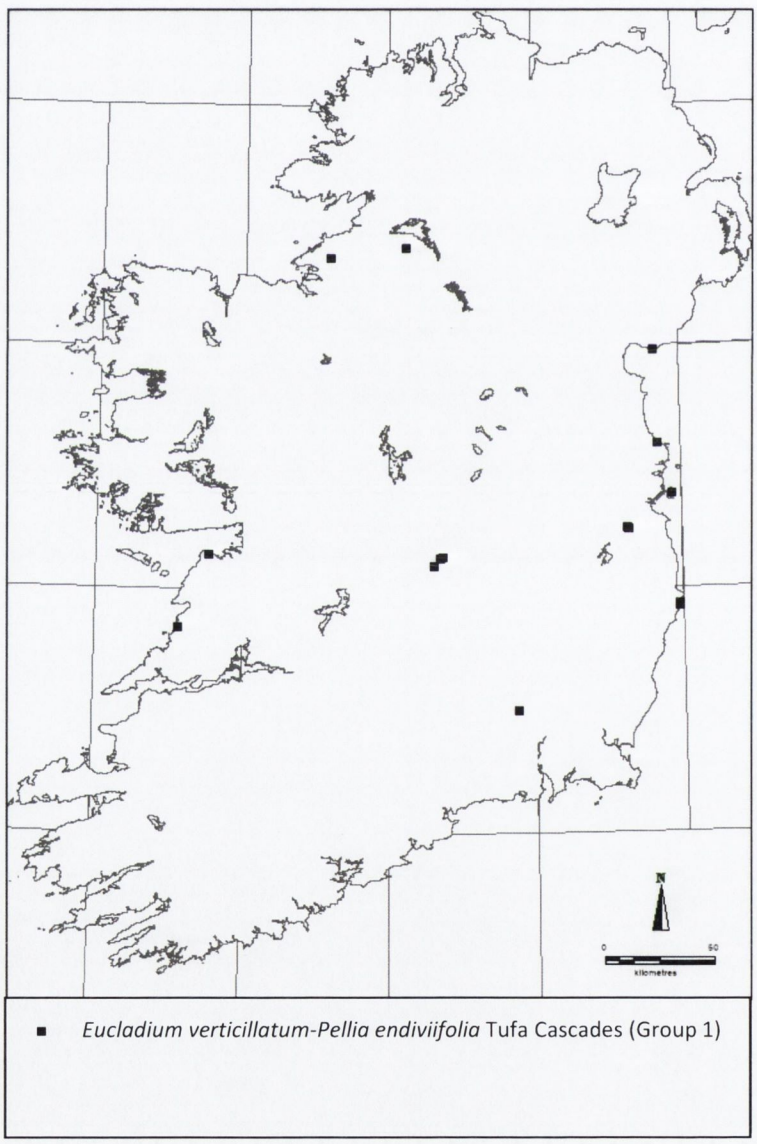
Tufa cascades predominate, occupying a mean of 89% of surface area, the highest proportion for any group (Fig. 3.6). Bare, unvegetated patches of tufa are often present (mean 24% of ground surface, Fig. 3.7), creating a striking appearance, sometimes with stalactites or intricate 'petrified' plant fragments (Photos 3.6 and 3.7). Stream crust tufa is present in 17% of samples although it occupies only 6% of surface area on average; there is no paludal tufa. The proportion of the ground surface lacking tufa is very low, at 5%.

This group occurs on the most steeply sloping sites (Fig. 3.9); the mean slope is 70°. Dripping water is characteristic and, occasionally, thin sheets of water flow over the surface of the tufa.

Leaf litter/standing dead vegetation is at its least in this group, covering only 3% of the ground surface (Fig.3.7).

3.2.1d Sample Locations

Five samples (28%) are from Co. Dublin (Map 3.1): three are inland, from woodland springheads in Glenasmole; two are from coastal sites, near Skerries and at Balscadden Beach, Howth (App. II). Four samples (22%) are from Co. Clare: three are in the coastal spray zone, from Spanish Point Beach; one is close to the coast, near Black Head in the Burren. Other coastal samples are from Ardmore, Co. Wicklow and Rathcor, Co. Louth. Three samples are from the Slieve Bloom Mountains; these are all situated on river banks (County River, Glenregan and Silver River). Other inland samples come from Dysart, Co. Kilkenny, a river bank near Kilgarrow, Co. Fermanagh and a waterfall at Gleniff, Co. Sligo.



Map 3.1: Locations of *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades (Group 1; n=18). See Appendix II for list of samples.

3.2.1e Typical Samples

QL154 Skerries (MC 100%)

This heavily petrified springhead occurs on the coast north of Skerries, Co. Dublin (Photo 3.1). *Palustriella commutata* is plentiful on the gently sloping upper part of the cascade, but most of the sheer face is occupied by *Eucladium verticillatum* with small amounts of *Didymodon tophaceus* and *Festuca rubra*. The red alga, *Chroothece* sp. also occupies part of this vertical surface, immediately adjacent to the relevé (Photo 3.2, 3.3). *Eucladium verticillatum* thrives best where slightly shaded, either by overhanging grasses or in crevices in the tufa. At the base of the cascade, pebbles from the beach have become incorporated into the rapidly forming tufa, constituting 'cemented rudites' (*e.g.* Pentecost 1995).

QL013 Glenasmole (MC 100%)

This inland site occurs in a woodland clearing and is lightly shaded by some trees on the hillside above (Photo 3.5). The predominant species are *Palustriella commutata, Eucladium verticillatum* and *Pellia endiviifolia* along with smaller amounts of *Didymodon tophaceus* and *Bryum pseudotriquetrum*. Several species of vascular plants occur with low cover values: *Eupatorium cannabinum, Tussilago farfara, Agrostis stolonifera, Festuca rubra, Poa trivialis, Brachypodium sylvaticum, Carex flacca* and *Hedera helix*. Bare tufa occupied 20% of the sample area (Photo 3.6).

3.2.1f Syntaxonomy

Eucladium verticillatum-Pellia endiviifolia Tufa Cascades are closely linked to *Adiantion* communities, although *Adiantum capillus-veneris* is absent. There is a strong overlap in bryophyte species and the physiognomy of the communities is very similar, since both occur on steep, damp cliffs, irrigated by calcareous water. Most Group 1 samples lie outside the biogeographical range of *Adiantum capillus-veneris*.

3.2.2 *Palustriella commutata-Geranium robertianum* Springheads

Group 2 *Palustriella commutata-Geranium robertianum* Springheads are characterised by large mounds of *Palustriella commutata* on springhead tufa cascades on moderately steep slopes. They nearly always occur in woodland and *Geranium robertianum* is frequently present, often accompanied by *Pellia endiviifolia*.

This is a cohesive group, containing 26 samples, with a high mean silhouette width (0.16, Fig. 3.3).

3.2.2a Floristics

Palustriella commutata, a characteristic moss of wet, base-rich habitats, is a highly significant indicator of this group (ISA***, Table 3.2). Frequent in all groups, it is in Group 2 that it maintains consistently high cover values (25% to 90%) across all samples (Fig. 3.5). In most samples (77%), its large wefts occupy at least half of the relevé (Photo 3.8). *Geranium robertianum* and *Rubus fruticosus* are also highly significant indicators. *Geranium robertianum* occurs in 77% of samples although it rarely covers large areas (mean cover 4%). It is one of the few vascular plant species to root in consolidated tufa or within mounds of *P. commutata*. *Rubus fruticosus* is less frequent (III), occurring only as small shoots which seldom thrive when rooted on tufa (mean cover 2%).

Equisetum telmateia, Carex remota and *Chrysosplenium oppositifolium* are statistically significantly linked to this group although they are only occasionally present (Table 3.2). *E. telmateia* (III) is sometimes a conspicuous marker of spring locations, but in Group 2 springhead samples, it is seldom abundant (maximum cover 15%). It is more characteristic of flush and seepage zones and occurs in Groups 3 and 4 where, though less frequent, it is at times more abundant (maximum cover 60% and 25% respectively).

The thallose liverwort, *Pellia endiviifolia* is frequent (IV), typically on the shadiest parts of tufa cascades (mean cover 2%). The moss *Eucladium verticillatum* (III) colonises shaded vertical tufa surfaces (mean cover 1%).

Fraxinus excelsior seedlings are frequent (III, mean cover 0.4%). They avoid the most strongly tufaceous microhabitats but, even on weakly formed tufa, they do not seem to survive beyond the seedling stage; none exceeded 30cm in height.

Other woodland species occasionally present in these samples (constancy classes II and I) include *Hedera helix, Lonicera periclymenum, Glechoma hederacea, Brachypodium sylvaticum, Asplenium scolopendrium* and the moss *Thamnobryum alopecurum*.

Table 3.2: Summary of statistically significant Indicator Species and other frequently occurring species in *Palustriella commutata-Geranium robertianum* Springheads (Group 2).

ISA	Species	Frequency	Mean % Cover	Minimum % Cover	Maximum % Cover
***	*Palustriella commutata*	V	61	25	90
***	*Geranium robertianum*	IV	4	0.1	40
***	*Rubus fruticosus*	III	2	0.5	10
**	*Carex remota*	II	1	1	15
**	*Asplenium scolopendrium*	II	1	0.5	10
**	*Hedera helix*	II	1	0.1	3
*	*Equisetum telmateia*	III	2	0.1	15
*	*Chrysosplenium oppositifolium*	II	1	0.5	20
ns	*Fraxinus excelsior*	III	0.4	0.1	5
ns	*Poa trivialis*	II	0.2	0.1	1
	Pellia endiviifolia	IV	2	0.1	10
	Agrostis stolonifera	III	3	1	15
	Eucladium verticillatum	III	1	0.1	10

Overall, 76% of the ground surface is vegetated (joint highest with Group 6, Fig. 3.7). However, dominance by *Palustriella commutata* results in relatively low species diversity; the mean number of species per relevé is 14 (Fig. 3.9).

In terms of plant groups, therefore, bryophytes dominate the vegetation (Fig. 3.4), with total cover of 69% (joint highest with Group 6). Graminoids and forbs are approximately equal (9% and 8% respectively). Woody plants make a bigger contribution in this group than in any other, albeit only 3% of total ground cover.

3.2.2b Uncommon species

Adiantum capillus-veneris (Maidenhair fern)

Adiantum capillus-veneris is present in one sample, QL195 Glencar, Co. Leitrim (Photo 3.9), nestled amongst *Palustriella commutata* and *Sesleria caerulea* in a damp, tufaceous rock crevice.

Adiantum capillus-veneris has a mainly coastal distribution in Ireland, with most populations centred on the Burren, the Aran Islands and Counties Sligo and Donegal. There are a number of

inland records for the Glencar region of Counties Sligo and Leitrim (BSBI website). The relationship between *Adiantum capillus-veneris* stands of the Burren (Ivimey-Cook & Proctor 1966), European *Adiantion* communities and *Cratoneurion* vegetation is of importance (see Chapter 4).

3.2.2c Environmental Variables

These samples are strongly tufa-forming. Tufa cascades are the dominant form of deposition, occupying 70% of the ground surface (second only to Group 1; Fig. 3.6). Cascades are sometimes massive, measuring 100m^2 or more. Twelve relevés (46% of Group 2 samples) were recorded on tufa cascades that exceeded the 4m^2 relevé size, so that the entire ground surface within the relevé consists of solid cascade tufa (App. II).

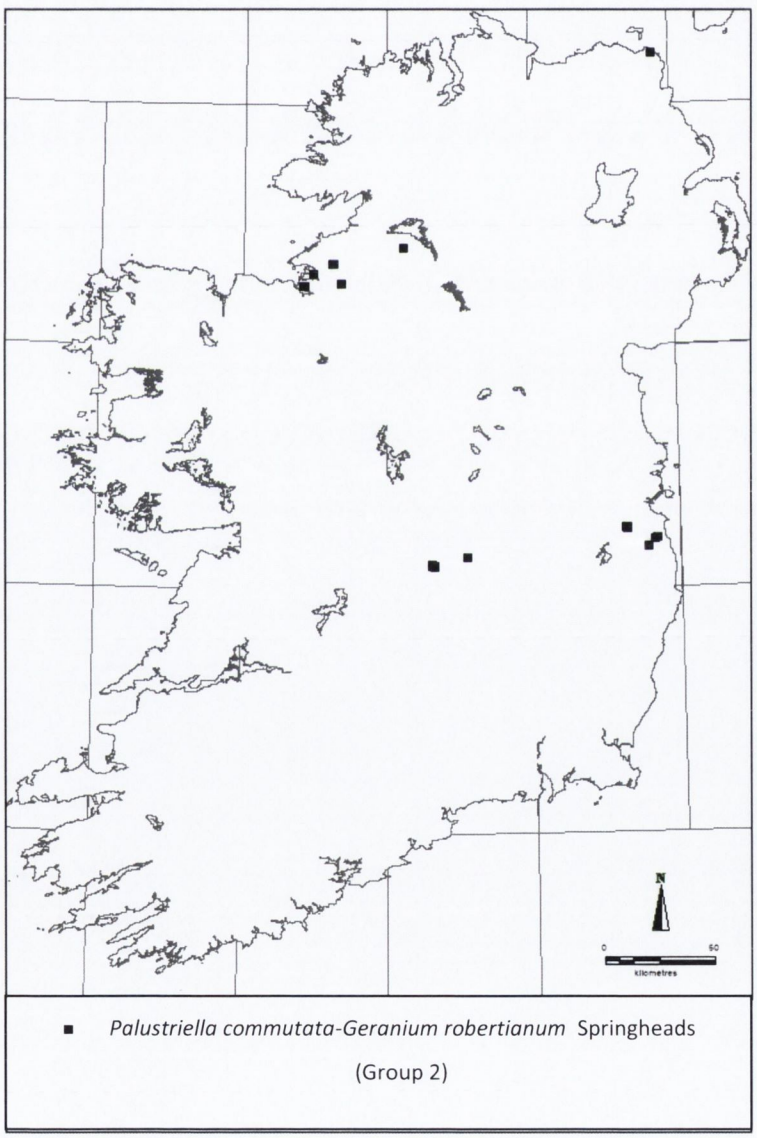
Other samples consist of smaller, more fragmented cascades combined with paludal tufa or oncoids/ ooids. In six samples (23%), paludal tufa predominates, mostly of intermediate to high strength. There is no stream crust tufa in this group and the proportion of ground lacking tufa is very low (3%, the lowest group value).

Slope is very variable (Fig. 3.9). Water sometimes drips or trickles slowly over the tufa, but mostly the surface is damp without obvious surface water (Fig 3.8) and dry ground is almost entirely absent from samples. Where dripping water is plentiful, for example in QL126 Knocknarea Glen (Photo 3.10), *Palustriella commutata* mounds are sometimes irrigated from above, as in the 'Cratoneuron Drip-Zone' facies (Ferreira 1978).

Canopy cover is high (mean cover 51%) and only Group 3 has a comparable level of shading (Fig. 3.9). Many samples are densely shaded; in one third of samples, canopy cover is ≥75%. Six samples (23%), however, are unshaded. Three of these are in an area where woodland was cleared some years previously (Camcor River valley) and one (Ballyman Glen) is in close proximity to woodland and scrub. The remaining two are in open coastal locations; one is north–facing near Murlough Bay in Co. Antrim. The other, at Ballincar, Co. Sligo, is south-facing, though somewhat shaded by overhanging herbaceous vegetation.

3.2.2d Sample Locations

Relevé locations are shown on Map 3.2. Nine samples (35%) are from the Slieve Bloom Mountains (altitude 148 – 190m): these are hillside or riverbank tufa cascades in woodland, or formerly wooded areas cleared in the recent past. Eight samples (31%) are from the north-west of Ireland: a dripping rock face and damp bank near Glencar and a spring head in Moneyduff Woods, Co, Leitrim; dripping limestone cliff faces in Knocknarea Glen and a coastal springhead at Ballincar, Co. Sligo; and a series of tufa dams and cascades on a stream at Kilgarrow, Co. Fermanagh. Five samples (19%) are from Co. Wicklow: three are from hillside springs in woodland at Knocksink and Knockree, and two are from the periphery of Ballyman Glen fen. Three samples are from springheads in Glenasmole, Co. Dublin.



Map 3.2: Locations of *Palustriella commutata-Geranium robertianum* Springhead relevés (Group 2; n=26). See Appendix II for list of samples.

3.2.2e Typical Samples

QL059 Glinsk (MC 99%)

This sample lies in a seepage zone on the bank of a small stream at Glinsk Grove, in the Camcor River valley, Slieve Bloom Mountains (Photo 3.11). Tufa occurs mostly as a solid, bryophyte-dominated cascade, with some oncoids/ooids, on a slope at 40°. *Palustriella commutata* occupies most of the surface (70%) with some small patches of *Didymodon tophaceus*, *Eucladium verticillatum* and *Pellia endiviifolia* (≤3% cover each). *Hedera helix* and *Rubus fruticosus* are located at the edge of the tufa formation and *Carex remota, Holcus lanatus, Poa trivialis* and *Geranium robertianum* are present in small quantities. It is shaded by *Quercus robur* (rooted on dry ground above the seepage) and *Hedera helix,* together forming a canopy of 80%.

On the opposite bank of the stream (QL060 Glinsk, MC 99%) water seeps through patchy tufa, which is in places consolidated into a cascade and elsewhere forms unconsolidated paludal tufa and oncoids/ooids (Photo 3.12). Here also *Palustriella commutata* is dominant and there are small patches of *Pellia endiviifolia* and *Brachythecium rivulare*, but bryophyte cover is incomplete and some bare tufa and soil are exposed. *Equisetum telmateia* is conspicuous (10% cover).

QL193 Moneyduff Wood (MC 97%)

This sample (Photo 3.8) occurs on gently sloping ground with strongly formed paludal tufa (bordering on consolidated cascade tufa). *Palustriella commutata* forms an almost continuous ground layer interspersed occasionally with *Asplenium scolopendrium, Carex remota, Geranium robertianum, Ranunculus repens, Cardamine pratensis, Ranunculus repens, Allium ursinum* and *Filipendula ulmaria*. Most of the ground surface is damp, without surface water, but a small stream trickles through, lined with oncoids. Canopy cover amounts to 70%, consisting of *Fraxinus excelsior* and *Fagus sylvatica* (rooted outside the relevé).

3.2.2f Syntaxonomy

Group 2 *Palustriella commutata-Geranium robertianum* Springheads fall between the *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977 and the *Equiseto telmatejae-Fraxinetum* Oberd. ex Seib. 1987 since the former lacks woodland species and the latter is characteristic of woodland flushes rather than spring heads (Oberdorfer 1977, 1992). Group 2 samples have little in common with the NVC *Palustriella commutata*-dominated springhead communities (M37 *Cratoneuron commutatum-Festuca rubra* Springs and M38 *Cratoneuron commutatum-Carex nigra* Springs, Rodwell 1998b) which occur in unshaded locations rather than in woodland.

3.2.3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes

Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes are characterised by the presence of trickling water in tufa-forming streams, waterfalls, flushes and seepage zones, with the mosses *Brachythecium rivulare*, *Platyhypnidium riparioides* and *Cratoneuron filicinum*. Tufa formation is very variable both in type and extent; tufa cascades are most frequent, but paludal tufa, oncoids/ooids, stream crust tufa, and tufa dams are also present.

This is a disparate group with the lowest mean silhouette width (-0.01, Fig. 3.3). There are 29 samples.

3.2.3a Floristics

Three species are highly significant indicators: *Brachythecium rivulare*, *Ranunculus repens* and a semi-aquatic moss, *Platyhypnidium riparioides* (syn. *Rhynchostegium riparioides*) (ISA***, Table 3.3). The first two species occur at the margins of small rivulets and on flushed ground. The third species occurs in flowing water although it is rarely fully submerged (Photo 3.14). It tolerates fluctuations in flow, persisting in streams which dry out intermittently. *Cratoneuron filicinum* (ISA*) is frequent, usually colonising drier edges. Both this species and *Platyhypnidium riparioides* sometimes dominate the vegetation, with maximum covers of 85% and 80% respectively. *Nasturtium officinale* agg. and *Apium nodiflorum*, also significant to the group, typically occur in shallow, slow-flowing water.

Palustriella commutata is frequent (IV, mean cover 8%), along with *Mentha aquatica, Geranium robertianum*, *Agrostis stolonifera* and *Pellia endiviifolia*.

Forbs make an important contribution to the vegetation (Fig. 3.4). They amount to 15% of ground cover while bryophytes occupy 32% of surface area (the lowest group value for bryophytes, jointly with Group 8). This ratio of forbs to bryophytes, almost 1:2, is higher than any other group. (Total cover of forbs in Group 6 is higher but, relative to other plant categories, they make a smaller contribution.) Mean cover of graminoids in Group 3 (14%) is approximately equal to that of forbs; in most groups, graminoids cover at least twice as much ground as forbs. Pteridophytes are more plentiful than in most groups, due to the presence of *Equisetum telmateia* (II).

Overall, species diversity is relatively low in this group, with 14 species per relevé on average (Fig. 3.9).

Table 3.3: Summary of statistically significant Indicator Species and other frequently occurring species in *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes (Group 3).

ISA	Species	Frequency	Mean % Cover	Minimum % Cover	Maximum % Cover
***	*Brachythecium rivulare*	V	4	0.1	40
***	*Ranunculus repens*	III	3	0.5	40
***	*Platyhypnidium riparioides*	II	6	0.1	80
*	*Cratoneuron filicinum*	IV	5	0.1	85
*	*Nasturtium officinale* agg.	II	5	0.5	55
*	*Apium nodiflorum*	I	1	3	10
*	*Glyceria notata*	I	1	0.1	25
	Agrostis stolonifera	V	5	0.1	25
	Palustriella commutata	IV	8	1	35
	Pellia endiviifolia	III	6	0.1	50
	Geranium robertianum	III	1	0.1	30
	Mentha aquatica	III	1	0.5	15
	Equisetum telmateia	II	5	0.1	60

3.2.3b Environmental Variables

The ground slopes somewhat more gently than in the previous two groups, with a mean slope of 27° (Fig. 3.9). Trickling water is present in 90% of samples, occupying 37% of the ground surface (Fig. 3.8). Half of the samples contain small pockets of impounded water with no discernible flow (mean 4% of ground surface). Dripping water rarely occurs since there are few steep surfaces in this group and water is mostly channelled into rivulets.

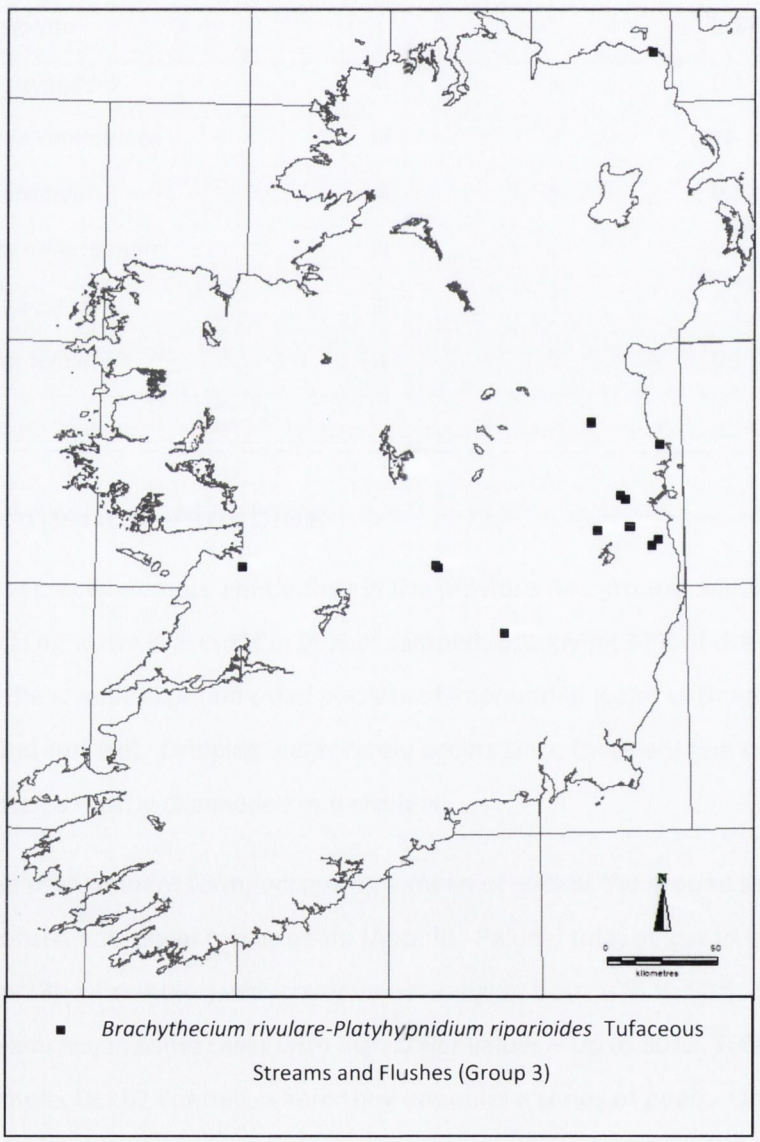
Cascade tufa is the predominant form, occupying a mean of 59% of the ground surface (Fig. 3.6). 41% of samples consist entirely of cascade tufa (App. II). Paludal tufa, of low to intermediate strength, occurs in 28% of samples, with cover values ranging from 10% to 50%. Stream crust tufa occurs in 21% of samples, in some cases with high cover values – up to 80%. Tufa dams are present in one sample, QL157 Fonthill, where they impound a series of pools. Oncoids/ooids are most abundant in this group, occurring in 38% of samples and covering 8% of ground surface. Bare tufa is highest in this group (Fig. 3.7), occupying 29% of the ground surface. It is especially prevalent below flowing water.

Most samples are situated in woodland and the mean canopy cover is 50% (comparable to Group 2, Fig. 3.9). Overhead canopy is absent in 21% of samples, but most of these (five out of six samples) are lightly shaded by nearby trees.

Several of these samples have been modified to some extent by anthropogenic activities, but others are semi-natural, with no indications of interference. At three sites in Co. Dublin (PS022 near Skerries and PS018 and PS109 in the R. Liffey valley, Co. Dublin containing five relevés in total), the hydrology has been altered: two species-poor relevés were recorded on tufa formed below outfall pipes; a further two were impacted by road drainage inputs upstream of the relevé; and one was in the overflow of a golf course pond. One site, (Broadboyne Bridge, with three relevés) showed evidence of tree felling in the recent past. One site (Hartwell, with four relevés, described below) was located on a busy livestock farm.

3.2.3c Sample Locations

Thirteen samples (45%) are located in Co. Dublin (Map 3.3): eight are hillside flushes, seepages and small streams in Glenasmole; four are small streams at Fonthill and Woodlands in the Liffey valley, in which the hydrology has been modified by land drainage or landscaping; one is below a pipe outfall on the coast near Skerries. Four samples are from Co. Wicklow: three are hillside seepages and flushes at Knockree; one is an unusual tufa cascade near Knocksink Wood. Four samples are from a massive but atypical tufa cascade near Naas, Co. Kildare, and a further three are from an equally large and unusual tufa cascade in Co. Meath. Two samples are from the Slieve Bloom Mountains and there is one each from Co. Antrim, Co. Kilkenny and the Burren.



Map 3.3: Locations of *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Stream and Flush relevés (Group 3; n=29). See Appendix II for list of samples.

3.2.3d Typical Samples

QL188 Glenasmole (MC 96%)

This small stream flows from a large spring complex in Glenasmole, Co. Dublin (Photo 3.15; see also TB07, Chapter 7 and Photos 7.11 and 7.12). Tufa accumulates rapidly as a series of cascades and stream crust, depending on the incline of the slope and the depth of water. This sample consists of 70% cascade tufa and 30% stream crust tufa with a mean slope of 20°. Flowing water occupies 40% of the surface area of the relevé and most of the tufa surface is unvegetated, especially where the water flow is most rapid. There is a dense overhead tree canopy, covering 95% of the relevé.

The most abundant species is *Equisetum telmateia*, which lines the edges of the stream. The uneven tufa surface creates various microhabitats for bryophytes. *Pellia endiviifolia* is the most abundant at 5%, with *Palustriella commutata*, *Brachythecium rivulare*, *Cratoneuron filicinum, Didymodon tophaceus, Pohlia wahlenbergii* and *Plagiomnium undulatum* in smaller quantities.

QL157 Fonthill Stream with Dams (MC 79%)

This small stream flows into the River Liffey near Palmerstown, Co. Dublin (Photo 3.16). It is heavily petrified in places, with a series of dams impounding pools along the length of the stream. The tufa is unusually dark in colour and the morphology suggests that it has been eroded in places (see Chapter 6, Photos 6.13 and 6.14). The outfall from a pipe, draining surface water from nearby roads and car parks, is located upstream of the tufa dams.

Vegetation is mostly confined to the dams and stream edges. *Palustriella commutata* is the most abundant species (10%), accompanied by the bryophytes *Brachythecium rivulare, Cratoneuron filicinum, Pellia endiviifolia, Conocephalum conicum* and *Platyhypnidium riparioides*. *Chrysosplenium oppositifolium* (2%) and *Ranunculus ficaria* (2%) are the most abundant vascular plants. Filamentous green algae (*Vaucheria* spp.) are conspicuous on the tufa dams. The overhead canopy cover is 50%, composed of *Fagus sylvatica, Acer pseudoplatanus, Fraxinus excelsior* and *Crataegus monogyna*.

QL053 Knockree (MC 74%)

In this sample, a small stream trickles below one of a series of seepages at Knockree, Co. Wicklow, over a 25° slope (Photo 3.13). The stream is lined with oncoids/ooids and stream crust tufa which are mostly unvegetated. Paludal tufa forms amongst tufts of vegetation, dominated by *Palustriella commutata* and *Agrostis stolonifera* (cover 25% each). Other bryophytes present are

Brachythecium rivulare, *Cratoneuron filicinum*, *Pellia endiviifolia* and *Platyhypnidium riparioides* (cover ≤3% each). Vascular plants include *Carex remota* and *Brachypodium sylvaticum* (cover 5% each), along with smaller amounts of *Ranunculus repens, R. ficaria, Geranium robertianum, Mentha aquatica, Cardamine pratensis, C. flexuosa* and *Lysimachia nemorum*.

QL172 – QL175 Hartwell Cascade (MC 85% - 96%)

These atypical samples recorded near Naas, Co. Kildare are not easily accommodated in existing *Cratoneurion* communities, yet they are located on a substantial, rapidly accumulating tufa cascade (Photo 3.17, see also Photos 6.9 to 6.12, 7.15, 7.16, 7.21 and 7.22). The cascade, measuring approximately 100m^2, is located on the bank of the Hartwell River in Co. Kildare and fed by a small stream draining lowland pasture. It has a lush growth of species not normally associated with tufa: *Petasites hybridus, Holcus lanatus, Scrophularia auriculata* and even nutrient-demanding species such as *Urtica dioica* and *Dactylis glomerata*. *Nasturtium officinale* agg., *Apium nodiflorum* and *Ranunculus repens* are abundant in the wettest parts where water trickles over the cascade. Beneath this often dense layer of vascular plants are intermittent patches of *Palustriella commutata, Cratoneuron filicinum* and *Brachythecium rivulare*, particularly in the wetter areas.

See Appendix VIII for further details of this site.

3.2.3e Syntaxonomy

Group 3 samples have affinities with Ivimey-Cook and Proctor's (1966) Calcareous Spring Communities from the Burren and with Oberdorfer's *Equiseto telmatejae-Fraxinetum* (Oberdorfer 1992), although in both cases, frequencies of species vary. The constant species and the significant indicator species of Group 3 are better represented in the Burren Calcareous Spring samples than in Oberdorfer's woodland community.

3.2.4 *Palustriella commutata-Agrostis stolonifera* Springheads

Group 4 *Palustriella commutata-Agrostis stolonifera* Springheads consist of hillside springheads, seepages and flushes dominated by *Palustriella commutata*, with *Festuca rubra* and *Agrostis stolonifera*, usually in unshaded places. Accompanying species are varied but most often consist of wetland generalists such as *Filipendula ulmaria, Juncus articulatus, Carex flacca* and *Calliergonella cuspidata*.

This is a somewhat disparate group with a low mean silhouette width of 0.04 (Fig. 3.3). There are 28 samples; most (71%) have membership coefficients of less than 80%.

3.2.4a Floristics

Species composition is variable and there are no very highly significant Indicator Species. The statistically significant indicators of the group, of which *Agrostis stolonifera* and *Filipendula ulmaria* (ISA **) are most frequent, have relatively broad ecological ranges; they are companion species to the *Cratoneurion* rather than character species and they do not provide a distinctive core to this group.

Palustriella commutata is constant (V) and is the dominant species in the group, with a mean cover of 37%, followed by *Festuca rubra* (10%) and *Carex flacca* (8%). After Group 2, this is the group in which *P. commutata* is most frequent and abundant (Fig. 3.5, Table 3.10). Other frequently occurring species in Group 4 are *Mentha aquatica, Juncus articulatus, Calliergonella cuspidata, Cratoneuron filicinum* and *Bryum pseudotriquetrum*.

Within this group, a subset of samples consists of springheads dominated by *Palustriella commutata* (cover 25% to 95%, Photo 3.18). These are, in effect, the unwooded equivalent of Group 2, lacking woodland plants such as *Geranium robertianum, Rubus fruticosus* and *Hedera helix*, and instead containing *Festuca rubra*. Other samples consist of diffuse seepages and flushes; in these, *Filipendula ulmaria, Eupatorium cannabinum, Crepis paludosa, Agrostis stolonifera, Carex flacca, Equisetum telmateia, Brachythecium rivulare* and *Calliergonella cuspidata* are more abundant. *Palustriella commutata* is usually present in these seepages and flushes, but with somewhat lower cover values (up to 45%).

Ranunculus flammula and *Juncus inflexus* are significant indicators (ISA *), but occur only occasionally (II). *Crepis paludosa* and *Eupatorium cannabinum* have their highest ISA indicator values in this group but they are not statistically significant.

This group is more diverse in species composition than Groups 1 to 3, with a mean of 20 species per relevé (Fig. 3.9). Overall, bryophytes contribute the greatest amount of cover (56%), but graminoids are also prominent (33% cover, Fig. 3.4).

Table 3.4: Summary of statistically significant Indicator Species and other frequently occurring species in *Palustriella commutata-Agrostis stolonifera* Springheads (Group 4).

ISA	Species	Frequency	Mean % Cover	Minimum % Cover	Maximum % Cover
**	*Agrostis stolonifera*	V	3	0.5	10
**	*Filipendula ulmaria*	III	1	0.5	10
*	*Juncus inflexus*	II	2	1	10
*	*Ranunculus flammula*	II	1	0.1	10
ns	*Eupatorium cannabinum*	II	4	2	45
ns	*Crepis paludosa*	I	1	2	10
	Palustriella commutata	V	37	10	95
	Festuca rubra	V	10	0.1	55
	Carex flacca	IV	8	0.5	35
	Calliergonella cuspidata	IV	6	0.1	30
	Juncus articulatus	IV	3	0.1	20
	Cratoneuron filicinum	III	3	0.1	50
	Bryum pseudotriquetrum	III	2	0.1	40
	Mentha aquatica	III	1	0.1	10

3.2.4b Environmental Variables

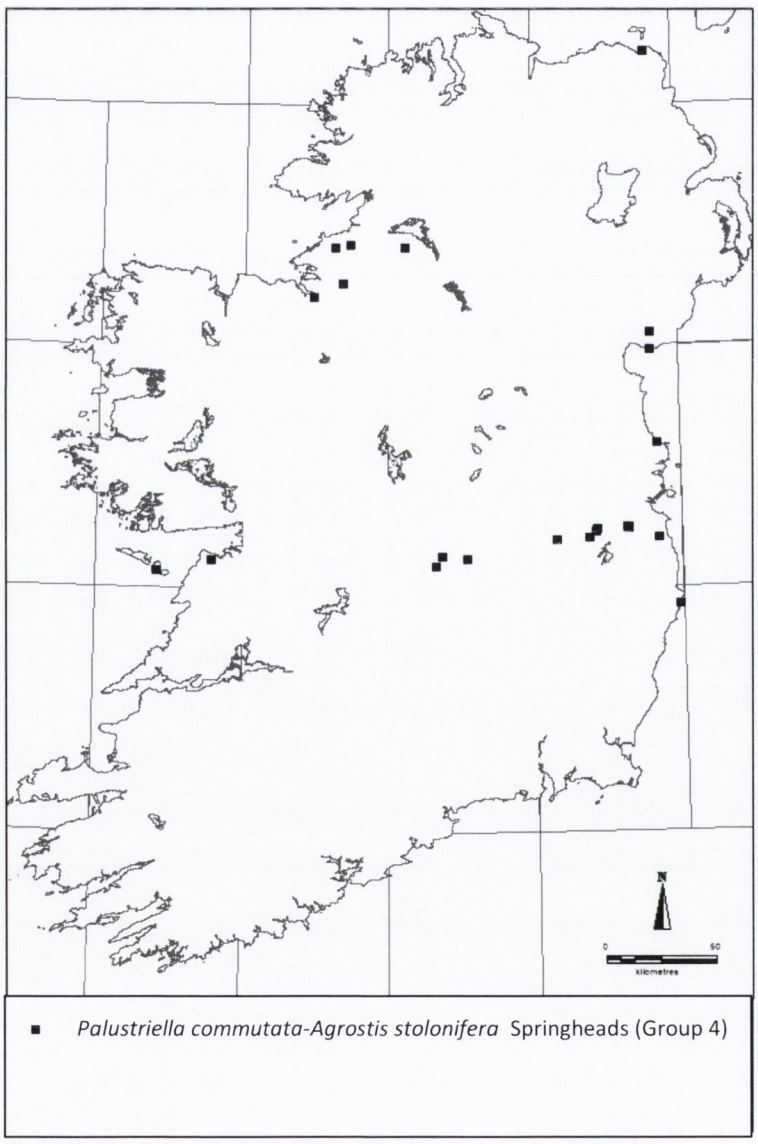
The extent of tufa formation in Group 4 samples is variable. 39% of samples contain tufa over the entire relevé surface area, but several samples have very low tufa cover (in two cases only a trace of tufa is present). Paludal and cascade tufa are present in approximately equal quantities (38% and 36% of ground surface respectively, Fig. 3.6). Paludal tufa is somewhat more frequent, occurring in 71% of samples, while cascade tufa is present in 50% of samples. The strength of paludal tufa is variable, but most often it is intermediate or strongly formed.

Slope is variable, ranging from 0° to 80°, with a mean of 26° (Fig. 3.9). In most cases, the ground surface is damp as water seeps through the soil just below the surface (75% cover, Fig. 3.8). Occasionally, it emerges above the ground surface, forming small rivulets (12%) or becoming impounded in pools (5%).

18% of samples are situated in woodland; canopy cover ranges from 5% to 80% (App. II). Most samples have no canopy cover and the mean canopy cover for the group as a whole is 9% (Table 3.9). Four samples (14%) are in the coastal spray zone and a further three (11%) are within 100m of the high tide mark.

3.2.4c Sample Locations

These samples have a wide geographic range, spread over 12 counties (Map 3.4). Seven samples (25%) are from Co. Dublin: most of these are diffuse springheads in Glenasmole; one is a springhead on the coast of north Co. Dublin near Skerries. Five samples (18%) are from Co. Kildare: one is an upwelling spring in Pollardstown Fen; the others are seepages and an upwelling spring near Naas. Three samples are seepages and flushes from varied locations within the Slieve Bloom Mountains. A further three are springheads and seepages from the coast in Co. Louth. Two are springheads in karst limestone, one in the Burren and the other on Inis Meáin. There are one or two samples each from Counties Antrim, Fermanagh, Sligo, Leitrim and Wicklow.



Map 3.4: Locations of *Palustriella commutata-Agrostis stolonifera* Springhead relevés (Group 4; n=28). See Appendix II for list of samples.

3.2.4d Typical Samples

QL063 Glenasmole (MC 97%)

This sample occurs on the hillside in Glenasmole in an area irrigated by a combination of diffuse seepage and flushing from above. The mean slope within the samples is 30° but the microtopography varies from flat ground with small pools to steep tufa surfaces with dripping water (Photo 3.19). A trickling rivulet covers half of the sample area. The entire sample consists of tufa, mostly cascade tufa, with a small amount of oncoids/ooids. About one third of the relevé is exposed as bare, unvegetated tufa. Bryophytes dominate the vegetation and the most abundant species, *Palustriella commutata,* occupies 45% of the surface area. Also plentiful are *Calliergonella cuspidata* and *Bryum pseudotriquetrum* along with the vascular plants *Eupatorium cannabinum, Festuca rubra, Deschampsia cespitosa, Agrostis stolonifera, Carex flacca* and *Juncus articulatus*. Total cover of graminoids is 15% and of forbs is 10%. The area is lightly shaded by *Fraxinus excelsior* growing nearby.

A nearby sample, QL062 (MC 90%), located uphill from QL063 in a less shaded part of the same flush, is more grassy in appearance (65% graminoid cover), but has an underlayer of *Palustriella commutata* and *Calliergonella cuspidata*. Additional species present in this sample are *Triglochin palustris, Filipendula ulmaria, Mentha aquatica, Festuca arundinacea, Juncus inflexus, Equisetum telmateia, E. palustre, Brachythecium rivulare* and *Plagiomnium elatum*.

QL153 Skerries (MC 96%)

This relevé, in north Co. Dublin, is situated in the coastal spray zone (Photo 3.20). It consists of a springhead tufa cascade, inclined at 45°, dominated by *Palustriella commutata* (65% cover), with smaller amounts of *Eucladium verticillatum*, *Calliergonella cuspidata* and *Cratoneuron filicinum*. Graminoids are conspicuous (40% cover), and include *Festuca rubra, Agrostis stolonifera, Carex flacca, Juncus articulatus* and *J. inflexus*. Forbs make a minor contribution (3% cover), mostly consisting of *Eupatorium cannabinum* and *Tussilago farfara.* The surface is mostly damp, with a minor contribution by dripping and trickling water (1% each).

3.2.4e Syntaxonomy

Group 4 *Palustriella commutata-Agrostis stolonifera* Springheads have much in common with Ivimey-Cook & Proctor's (1966) Calcareous Spring Communities of the Burren. Of my eight groups, this one comes closest to that Burren community. In terms of the British NVC, Group 4 samples are intermediate between the NVC communities M37 *Cratoneuron commutatum-Festuca rubra* springs, M38 *Cratoneuron commutatum-Carex nigra* springs and M10 *Carex dioica-Pinguicula vulgaris* mires (Rodwell 1998b).

3.2.5 *Schoenus* Springs

Schoenus nigricans dominates Group 5 samples and *Campylium stellatum* is the most abundant bryophyte. Graminoids and bryophytes cover the surface in equal measure. Strongly formed paludal tufa is characteristic and pools of water are often present (Photo 3.21). These springs occur on level ground and are unshaded. This is a cohesive group, with a high mean silhouette width (0.17, Fig. 3.3). Nine samples (41%) have membership coefficients of 100%.

3.2.5a Floristics

Schoenus nigricans is conspicuously dominant in the vegetation, often forming hummocks. It is present in all but one sample, with cover values ranging from 15% to 65% (mean 35%, Table 3.5). It is a very highly significant indicator, seldom occurring in samples outside Group 5 (see synoptic table, App. III). *Campylium stellatum* is also constant and, with mean cover of 22%, it is the most abundant bryophyte, although several other species are also characteristic of the group. *Scorpidium cossonii* and *S. scorpioides* are frequent, sometimes with high cover values, up to 50% and 65% respectively. The latter species is especially typical of shallow pools. *Ctenidium molluscum* is frequent (IV) but it seldom occupies large areas (cover ≤20%) and typically occurs in drier places, for example on the tops of hummocks. The grass *Molinia caerulea* is frequent, but with lower cover values than *S. nigricans* (mean 9%). All of the above named species are highly significant indicators of this group (ISA***).

Palustriella commutata and *P. falcata* each occur in approximately half the samples. *P. commutata* is usually more plentiful than *P. falcata*, with mean values of 8% and 1% respectively.

The graminoid layer also contains *Festuca rubra*, *Phragmites australis*, *Carex panicea*, *C. lepidocarpa*, *C. pulicaris*, *C. hostiana* and *Eriophorum latifolium*. These species are present in small amounts, with mean cover values of up to 3%. *P. australis*, where present, occurs as scattered, somewhat stunted shoots, never reaching dominance. Forbs and other non-graminoid vascular plants make a small contribution. Most frequently occurring are *Selaginella selaginoides, Pinguicula vulgaris, Anagallis tenella, Potentilla erecta* and *Succisa pratensis* (each in constancy class III), along with occasional *Pinguicula lusitanica, Cirsium dissectum, Potamogeton coloratus, Samolus valerandi* and *Dactylorhiza fuchsii*. Two calcifuge species, *Calluna vulgaris* and *Drosera rotundifolia*, are present at low frequency, in 18% and 14% of samples respectively. They colonise microhabitats such as hummock tops which have least contact with the calcareous spring water. The stonewort, *Chara vulgaris*, is present in 18% of samples, covering 30% of the surface of one sample (QL094 Dooaghtry).

Table 3.5: Summary of statistically significant Indicator Species and other frequently occurring species in *Schoenus* Springs (Group 5).

ISA	Species	Frequency	Mean % Cover	Minimum % Cover	Maximum % Cover
***	*Schoenus nigricans*	V	35	15	65
***	*Campylium stellatum*	V	22	1	65
***	*Molinia caerulea*	IV	9	1	40
***	*Ctenidium molluscum*	IV	4	0.1	20
***	*Scorpidium scorpioides*	III	10	2	65
***	*Scorpidium cossonii*	III	5	0.1	50
***	*Potentilla erecta*	III	1	0.1	5
**	*Selaginella selaginoides*	III	0.2	0.1	1
**	*Phragmites australis*	II	0.3	0.1	3
*	*Carex pulicaris*	II	0.5	1	5
*	*Cirsium dissectum*	I	0.3	0.1	5
*	*Pinguicula lusitanica*	I	0.1	0.1	1
*	*Calluna vulgaris*	I	0.2	0.1	3
*	*Drosera rotundifolia*	I	0.1	0.1	2
ns	*Chara vulgaris*	I	2	1	30
ns	*Potamogeton coloratus*	I	0.2	1	3
ns	*Samolus valerandi*	I	0.2	0.5	3
ns	*Carex hostiana*	I	0.2	0.5	3
ns	*Eriophorum latifolium*	I	0.1	1	1
ns	*Dactylorhiza fuchsii*	I	<0.1	0.1	0.5
	Palustriella commutata	III	8	0.5	55
	Carex lepidocarpa	III	3	0.1	20
	Festuca rubra	III	3	0.5	40
	Succisa pratensis	III	2	0.5	20
	Palustriella falcata	III	1	1	10
	Carex panicea	III	1	0.1	10
	Aneura pinguis	III	0.5	0.1	5
	Pinguicula vulgaris	III	0.4	0.5	2
	Anagallis tenella	III	0.4	0.1	2

Overall species diversity is moderately high, with a mean of 22 species per sample (Fig. 3.9). There are 14 statistically significant indicator species (Table 3.5), half of which are highly significant (ISA ***). The proportion of graminoid cover in the vegetation is high (mean cover 54%), almost equalling that of bryophytes (55%, Fig. 3.4). Forbs cover on average 8% of the surface. Standing dead vegetation is characteristic, occurring in all samples (minimum cover 2%) and with a mean value of 28% cover, the highest group mean (Fig. 3.7).

3.2.5b Uncommon species

Leiocolea bantriensis

The leafy liverwort *Leiocolea bantriensis* occurs in one sample in Group 5, QL072 Keelhilla, Burren (and also in one Group 8 sample, QL133 Gleniff). At Keelhilla, it occurs in species-rich springs with *Schoenus nigricans, Eriophorum latifolium* and *Pinguicula lusitanica*. Accompanying bryophytes include *Breutelia chrysocoma, Palustriella commutata, Philonotis calcarea* and *Aneura pinguis*. There is a pronounced hummock/hollow pattern to the vegetation (Photo 3.22). The status of *Leiocolea bantriensis* in Ireland is Near Threatened. It occurs in 19 vice-counties, especially those near north and west coasts. It requires permanently wet, calcareous sites and it is likely that this species has declined due to habitat loss (Lockhart *et al.* 2012).

Dactylorhiza majalis ssp. *traunsteineroides*

Dactylorhiza majalis subsp. *traunsteineroides* occurs in two Group 5 samples, QL089 Rinnamona in the Burren and QL096 Eskeragh, Co. Mayo. *Pinguicula vulgaris, Schoenus nigricans, Molinia caerulea, Carex pulicaris, Palustriella falcata, Campylium stellatum* and *Ctenidium molluscum* are present in both of these samples. Both sites are typical of the characteristic calcareous fen habitat of this plant (Curtis & Thompson 2009) and both form paludal tufa. *D. majalis* subsp. *traunsteineriodes* is widespread but local in Ireland, occurring mainly across central Ireland, from the Burren, Galway and Mayo through the midlands to Wicklow, Dublin and Louth (Curtis & Thompson 2009).

Eriophorum latifolium

Eriophorum latifolium occurs in two samples in Group 5 (as well as one each in Groups 4 and 6, App. III). In each case, these samples are in fens with weak to intermediate paludal tufa. The most frequent associates in these four samples are *Carex lepidocarpa* (in all four samples), as well as *Succisa pratensis, Festuca rubra, Schoenus nigricans, Carex panicea, C. flacca, Palustriella commutata, Campylium stellatum, Bryum pseudotriquetrum* and *Calliergonella cuspidata* (each in three samples). *Eriophorum latifolium* is widespread but rather rare in Ireland (Parnell & Curtis 2012); it is largely confined to fens and flushes.

3.2.5c Environmental Variables

Paludal tufa is at its most abundant in this group (Fig. 3.6) and it is often very heavily precipitated, forming a conspicuous white, crunchy layer on the ground surface with occasional oncoids and ooids. Paludal tufa occupies, on average, 59% of the ground surface and of this, 53% is strongly formed. Cascade tufa is entirely absent and stream crust tufa occurs in only one sample. However, the degree to which tufa is formed is highly variable and the proportion of surface area lacking tufa is relatively high (mean cover 37%). Two samples which are highly characteristic of this group (from Ballycurrin Fen, both with membership coefficients 100%) are almost devoid of tufa, with only a trace occurring on plant stems. In other characteristic samples (Eskeragh and Corhawnagh, also with membership coefficients of 100%) the surface consists entirely of strongly precipitated paludal tufa.

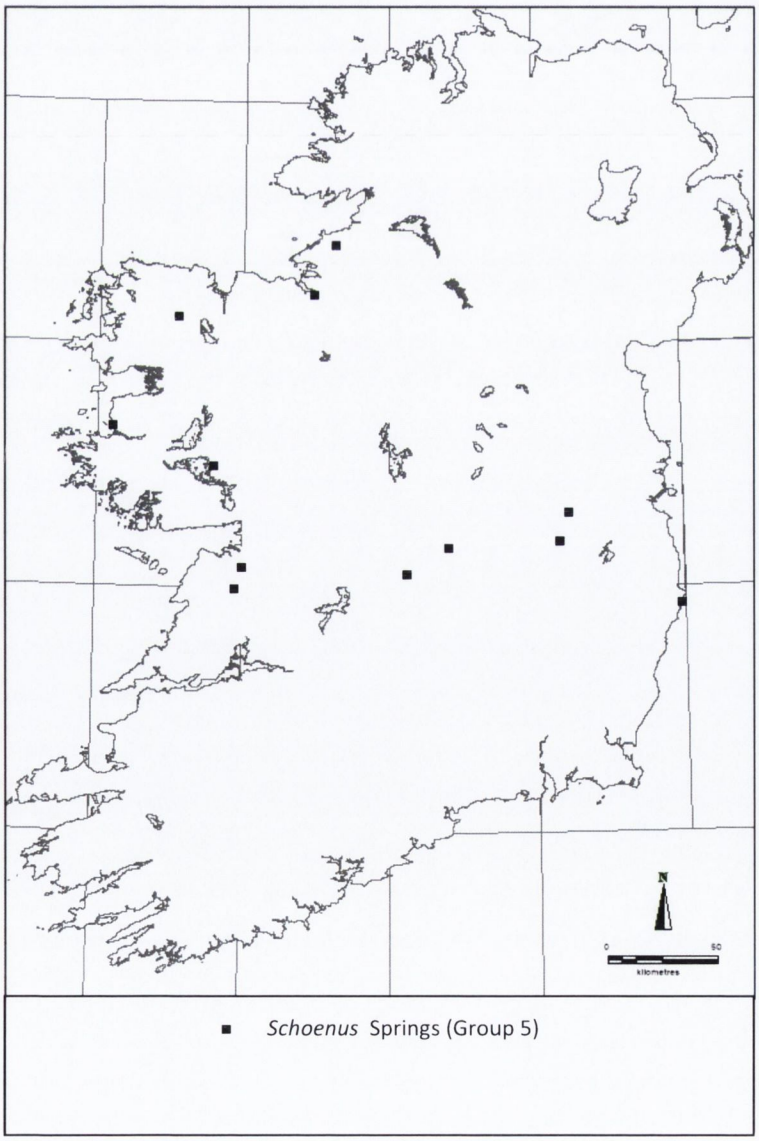
These springs nearly always occur on level ground. The mean slope is 5° (joint lowest group mean with Group 6, Fig. 3.9) and 77% of samples have a slope of less than 5°. Three samples (14%) are on steep slopes (inclined at 15° to 65°): two are at an unusual, species-rich site, Cormac Reagh's Hole in Co. Sligo, where a small stream trickles over boulders, flanked by a *Schoenus*-rich flush (Photos 3.24 and 3.25); one is on coastal seepage at Ardmore, Co. Wicklow.

Pools are characteristic, and this group has the highest mean cover by pools (mean 19% of ground surface, Fig. 3.8). Trickling water is at its lowest in this group (mean 2% of ground surface), although one exceptional sample (at Cormac Reagh's Hole) contains a trickling stream occupying 35% of ground surface. There is no dripping water.

The proportion of bare, unvegetated ground is relatively low (19%) and bare tufa is intermediate compared to other groups, at 14% (Fig. 3.7). All sites are open, lacking any woody canopy cover or shading.

3.2.5d Sample Locations

This group has a somewhat more westerly distribution than the previous groups (Map 3.5). Eight samples (36%) are from Co. Mayo: four come from Ballycurrin Fen, in south Mayo, close to the east shore of Lough Corrib; three are from Eskeragh in north-west Mayo and one is from near the coast at Dooaghtry. Five samples (23%) are from Co. Sligo: three are from Corhawnagh at the north-eastern end of the Ox Mountains; two are from Cormac Reagh's Hole at the foot of Tievebaun Mountain in the Benbulbin Range. The remaining samples are from fens in the Burren (Keelhilla and Rinnamona), Kildare (Pollardstown and Ballynafagh), Offaly (Lisduff) and Laois (near Clonaslee) and from a coastal seepage at Ardmore, Co. Wicklow. The Clonaslee sample (QL149) was collected from the same locality as that of Tüxen's, in 'a lime-rich, cold spring at the foot of an esker near Clonaslee', Co. Offaly (Braun-Blanquet & Tüxen 1952); however, there are few shared species and my sample is less calcicole in character than the original.



Map 3.5: Locations of *Schoenus* Spring relevés (Group 5; n=22). See Appendix II for list of samples

3.2.5e Typical Samples

QL095 Eskeragh (MC 100%)

This Co. Mayo sample is located in a heavily petrified spring area on level ground surrounded by blanket bog. Paludal tufa forms as a thick, conspicuous white layer with occasional oncoids/ooids and shallow pools of water lie amongst clumps of *Schoenus* (Photo 3.23). *Schoenus nigricans* is the dominant species (40% cover) and *Campylium stellatum* is abundant (35%) along with *Palustriella commutata* (30%). *Molinia caerulea* covers 10% of the sample area. Other species occur with lower cover values; they include *Anagallis tenella, Succisa pratensis, Festuca rubra, Cladium mariscus, Carex lepidocarpa, C. panicea, Selaginella selaginoides, Palustriella falcata* and *Philonotis calcarea*.

Other samples from this site contain greater cover by *Schoenus nigricans* and *Campylium stellatum* but less *Palustriella* spp. Additional species in these samples include *Pinguicula vulgaris, P. lusitanica, Pedicularis palustris, Scorpidium scorpioides, S. cossonii, Fissidens adianthoides, Bryum pseudotriquetrum* and *Aneura pinguis*.

Very similar vegetation is found at Corhawnagh, Co. Sligo (Photo 3.21), in a spring-fed hollow at the base of the Ox Mountains, and at Ballycurrin, Co. Mayo east of Lough Corrib.

QL178 Lisduff Fen (MC 94%)

QL178, recorded at Lisduff Fen, Co. Offaly, contains similar vegetation to Eskeragh samples, but the sward is somewhat more mixed. *Schoenus nigricans* (20%) is accompanied by *Carex lepidocarpa* (10%) and *Molinia caerulea* (5%), along with smaller amounts of *Eriophorum latifolium, Eleocharis quinqueflora, Carex dioica, C. panicea* and *C. pulicaris*. A dense 'brown moss' layer covers 90% of the sample area, dominated by *Scorpidium cossonii* (50%) and *Campylium stellatum* (25%) along with *Scorpidium scorpioides, Palustriella falcata, Fissidens adianthoides* and *Calliergonella cuspidata*. Forbs are dominated by *Menyanthes trifoliata* (25%) with small amounts of *Triglochin palustris, Potentilla erecta* and *Valeriana officinalis*.

Localised patches of consolidated paludal tufa occur, along with occasional tufa-lined shallow pools and a more widely distributed sparse coating of tufa at the bases of plants.

QL132 Cormac Reagh's Hole, Co. Sligo (MC 64%)

This sample is not typical of Group 5 (it has partial membership of Groups 7, MC 14%, and Group 8, MC 12%), but it is ecologically interesting and physiognomically distinctive (Photos 3.24 and

3.25). It occurs in a small stream trickling over boulders at the foot of Tievebaun Mountain's northern slopes. Much of the surface is unvegetated (68%), consisting of bare oncoids/ooids and stream crust tufa as well as a small amount of bare stone. Water trickles over 35% of the ground surface.

Schoenus nigricans is the most abundant species (25% cover), forming small clumps around which the water flows. The rare moss *Seligeria oelandica* (see Group 8) is present with 2% cover. This setting is somewhat unusual for this species; it normally colonises flushed cliffs rather than streams. Here, it clings to the lee of tufa-coated boulders in the stream. *Pinguicula vulgaris, Molinia caerulea, Sesleria caerulea, Eriophorum angustifolium, Eleocharis quinqueflora, Juncus articulatus, Selaginella selaginoides, Palustriella commutata, P. falcata, Eucladium verticillatum, Jungermannia atrovirens* and *Aneura pinguis* all occur with cover ≤2%. The cyanobacterium *Rivularia* is plentiful (cover 10%).

The springhead from which this stream emanates is dominated by *Palustriella commutata* (95%, QL130) and falls into Group 4 (Photo 3.18).

3.2.5f Syntaxonomy

This group conforms to the *Schoenetum nigricantis* (Allorge 1922) Koch 1926 as it occurs in Irish fens and flushes (Ó Críodáin & Doyle 1997), with only minor differences in species frequencies. *Palustriella commutata* and *P. falcata* are somewhat more frequent and abundant in my Group 5 samples.

3.2.6 *Carex lepidocarpa* Small Sedge Springs

Group 6 *Carex lepidocarpa* Small Sedge Springs consist of small sedge vegetation in which *Carex lepidocarpa* is often conspicuous and *Palustriella commutata* and *Calliergonella cuspidata* are the dominant bryophyte species. Samples have high species diversity but are, on the whole, only weakly tufaceous. Paludal tufa is the predominant form but the proportion of the ground surface which lacks tufa is at its highest in this group.

Cohesion of the group is intermediate with a mean silhouette width of 0.09 (Fig. 3.3). With 30 samples, this is the largest group.

3.2.6a Floristics

Succisa pratensis, Carex lepidocarpa and *Calliergonella cuspidata* are highly significant indicators of the group (ISA ***) and are present at constancy classes V or IV (Table 3.6). *Anagallis tenella, Triglochin palustris, Pedicularis palustris* and *Equisetum palustre* are also highly significant indicators, although they occur less frequently (constancy classes III and II). Other species with high frequencies are *Festuca rubra, Carex panicea, C. flacca, Juncus articulatus* and *Palustriella commutata* (constancy classes V and IV).

Species richness is high (on average 27 species per relevé, Fig. 3.9) and there are 22 significant indicator species, of which seven (above) are highly significant. Only Group 8 has more species per relevé and more significant indicator species.

The vegetation typically consists of a sward of small sedges with a 'brown moss' underlayer (Photo 3.26). Bryophytes can be locally dominant with few sedges or, conversely, in the absence of grazing, sedges and rushes can expand to reduce bryophyte cover and diversity but overall, across these samples, graminoids and bryophytes provide similar levels of cover (means of 60% and 69% respectively, Fig. 3.4). Forbs amount to about one third of the cover of these groups (19%). This is the group with the least exposed bare ground (11%, Fig. 3.7); it has the highest cover of both graminoids and forbs and, along with Group 2, the highest cover of bryophytes (Fig. 3.4).

Table 3.6: Summary of statistically significant Indicator Species and other frequently occurring species in *Carex lepidocarpa* Small Sedge Springs (Group 6).

ISA	Species	Frequency	Mean % Cover	Minimum % Cover	Maximum % Cover
***	*Succisa pratensis*	V	5	0.5	25
***	*Carex lepidocarpa*	IV	12	2	45
***	*Calliergonella cuspidata*	IV	23	0.1	70
***	*Anagallis tenella*	III	2	0.1	20
***	*Equisetum palustre*	III	3	0.1	20
***	*Triglochin palustris*	II	2	0.1	20
***	*Pedicularis palustris*	II	1	0.5	10
**	*Juncus articulatus*	IV	5	0.1	25
**	*Eriophorum angustifolium*	III	1	0.1	10
**	*Mentha aquatica*	III	1	0.1	5
**	*Carex nigra*	II	1	0.1	20
**	*Epilobium parviflorum*	II	0.2	0.1	1
*	*Juncus subnodulosus*	II	7	3	75
*	*Bryum pseudotriquetrum*	II	2	0.1	20
*	*Cardamine pratensis*	II	1	0.1	10
*	*Plagiomnium elatum*	II	0.4	0.1	3
*	*Carex rostrata*	I	3	3	40
*	*Equisetum fluviatile*	I	2	0.1	60
*	*Menyanthes trifoliata*	I	2	1	40
*	*Carex disticha*	I	1	0.5	10
*	*Caltha palustris*	I	0.2	0.5	3
ns	*Eleocharis quinqueflora*	II	1	0.1	15
ns	*Carex dioica*	II	0.3	0.1	5
ns	*Hydrocotyle vulgaris*	I	2	0.1	35
ns	*Galium uliginosum*	I	0.1	0.1	1
ns	*Dactylorhiza incarnata*	I	<0.1	0.5	0.5
ns	*Isolepis cernua*	I	<0.1	0.1	1
	Festuca rubra	V	9	1	40
	Carex panicea	V	5	0.5	15
	Palustriella commutata	IV	23	1	80
	Carex flacca	IV	8	1	40
	Molinia caerulea	III	8	0.1	75
	Campylium stellatum	III	6	0.5	30
	Agrostis stolonifera	III	2	0.1	20
	Potentilla erecta	III	1	0.1	10
	Cirsium palustre	III	1	0.5	5
	Aneura pinguis	III	0.4	0.1	2

The more species-rich samples contain low-growing vegetation with *Anagallis tenella, Pedicularis palustris, Cardamine pratensis, Triglochin palustris, Festuca rubra, Carex lepidocarpa, C. panicea, C. dioica, Eriophorum angustifolium, Eleocharis quinqueflora, Palustriella commutata, Campylium stellatum, Bryum pseudotriquetrum* and *Aneura pinguis*. *Calliergonella cuspidata* is often present, but with low cover values (≤10%). Cover values of individual vascular plant species tend to be low (≤5%), although those of moss species (especially *Palustriella commutata*) are sometimes high (≥40%).

Where larger grasses and rushes dominate, smaller sedges and forbs are excluded and species diversity is lower. In such situations, *Juncus subnodulosus* is often present (cover ≥30%) along with *Phragmites australis, Juncus inflexus* and *Eupatorium cannabinum*. *Calliergonella cuspidata* is the dominant bryophyte (cover often ≥40%) and few other bryophyte species are present (see Section 6.1.3). These samples tend to be weakly tufa-forming; the extreme ecological conditions of strongly tufa-forming microhabitats prevent the above species from becoming dominant.

Group 6 standing dead vegetation is intermediate compared to other groups (mean cover 13%, Fig. 3.7), but it is very variable, ranging from <1% to 45% cover. Highest values are for Pollardstown Fen and Kingsbog (both in Co. Kildare).

3.2.6b Rare Species

Tomentypnum nitens

Tomentypnum nitens is present in one sample, QL204 Pollardstown Fen (cover 5%; see Photos 3.27 and 3.28). Associated bryophyte species are *Palustriella commutata, Scorpidium cossonii, Campylium stellatum, Bryum pseudotriquetrum, Calliergonella cuspidata* and *Plagiomnium elatum*. This sample was recorded along a narrow, species-rich track where occasional trampling (by wild animals) kept the vegetation more open than the adjacent areas on either side. Thus, *Juncus subnodulosus* and *Phragmites australis* are present but not dominant, accompanied by *Festuca rubra, Schoenus nigricans, Eriophorum latifolium, Carex lepidocarpa, C. panicea* and *C. flacca*. Forbs include *Succisa pratensis, Epipactis palustris, Pedicularis palustris, Galium uliginosum, Parnassia palustris* and *Caltha palustris*. In Pollardstown Fen, *T. nitens* tends to occur on damp ground that is not strongly tufaceous; it is absent from the most strongly tufa-forming parts.

Tomentypnum nitens is Vulnerable in Ireland. Besides Pollardstown Fen, it occurs locally in wet calcareous habitats such as fens and base-rich flushes in blanket bogs in northwest Mayo,

Donegal, Galway, Limerick and Westmeath. It is common in Arctic and Boreal zones and exists in Ireland as a glacial relict (Porley & Hodgetts 2005). It has declined in Ireland and Britain in the past few decades, and has become extinct in Northern Ireland. It is vulnerable to drainage, removal of grazing and eutrophication of waters (Lockhart *et al.* 2012).

3.2.6c Environmental Variables

Paludal tufa is the dominant form, occupying on average 51% of ground surface (Fig. 3.6). It occurs in 93% of samples (App. II). Strength of precipitation is variable, but most is at intermediate levels (36% mean cover). Cascade tufa is absent and stream crust tufa occurs in only two samples (7%). The proportion of the ground surface lacking tufa ('non-tufa' 45%) is greater in this group than in any other. One sample lacks tufa; two samples (7%) have just a faint trace on the stems of plants. This group also has the lowest proportion of bare, unvegetated tufa, with a mean of 7% cover (Fig. 3.7).

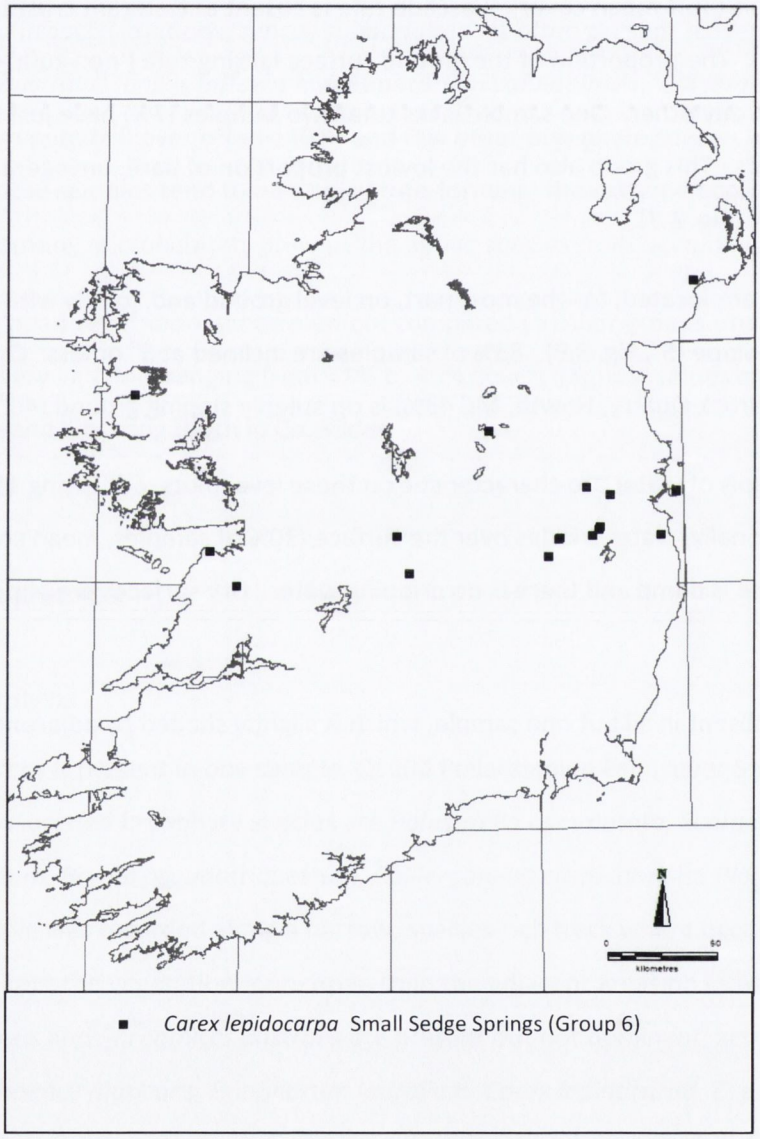
Group 6 samples are located, for the most part, on level ground and, jointly with Group 5, have the lowest mean slope (5°, Fig. 3.9). 83% of samples are inclined at 5° or less. One atypical sample (QL165 Kilrock Quarry, Howth, MC 43%) is on steeply sloping ground (40°).

Shallow, static pools of water are characteristic on these level plots, occupying 11% of the surface (Fig. 3.8). Occasionally, water trickles over the surface (30% of samples, mean cover 6%). Most of the ground surface is damp and there is no dripping water. Dry surfaces are almost entirely absent.

Canopy cover is absent in all but one sample, which is slightly shaded by adjacent hazel scrub.

3.2.6d Sample Locations

Half of the samples in this group (15 samples) are from diffuse springs, fens and flushes in Co. Kildare: Pollardstown Fen (4 samples); Louisa Bridge, Leixlip (5 samples); King's Bog, near Kildare town (1 sample); and a number of small sites near Naas (5 samples, Map 3.6). Four samples (13%) are from diffuse springs at Faughalstown in Co. Westmeath. Counties Dublin, Wicklow, Offaly, Clare, Meath, Mayo and Down are represented by one or two samples each.



Map 3.6: Locations of *Carex lepidocarpa* Small Sedge Spring relevés (Group 6; n=30). See Appendix II for list of samples.

3.2.6e Typical Samples

QL163 Faughalstown (MC95%)

This is one of four samples (all belonging to Group 6) from a species-rich site on the shores of Lough Derravaragh (Photo 3.29). In this sample, graminoids are most conspicuous. *Festuca rubra* covers 30% of the surface, along with *Carex lepidocarpa* and *Juncus articulatus* (10% each) and smaller amounts of *Carex panicea, C. flacca, C. rostrata, C. dioica, Eleocharis quinqueflora, Schoenus nigricans* and *Eriophorum angustifolium*. Bryophytes cover an equal area. *Palustriella commutata* is most abundant (30% cover) along with *Campylium stellatum, Ctenidium molluscum, Calliergonella cuspidata* and small amounts of *Philonotis calcarea, Bryum pseudotriquetrum* and *Aneura pinguis*. *Succisa pratensis* is the most abundant forb (10% cover) and *Anagallis tenella, Parnassia palustris, Pinguicula vulgaris* and *Triglochin palustris* are also present, along with *Selaginella selaginoides* and *Chara vulgaris*.

Paludal tufa of intermediate strength covers 95% of the surface area. Pools occupy 10%, and 90% of the surface is damp. The ground surface is inclined at 5°.

Other relevés from this spring complex illustrate the range of ecological variation:

QL161 (MC 95%) has lower tufa cover (50% cover), *Carex rostrata* is the dominant vascular plant and *Calliergonella cuspidata* the most abundant bryophyte. Forbs include *Pedicularis palustris, Mentha aquatica* and *Hypericum tetrapterum*.

QL162 (MC 53%, Photo 3.30) is more strongly tufa forming. Flushing is evident at this location, unlike nearby samples. 25% of the surface consists of bare, paludal tufa; water trickles over 10% of the surface and pools occupy 25%. Bryophytes are more conspicuous and graminoid cover is lower than in QL163. *Palustriella commutata* is the most abundant species (30% cover). *Philonotis calcarea* and *Bryum pseudotriquetrum* cover 10%. The most abundant vascular plants are *Festuca rubra, Carex lepidocarpa* and *Nasturtium officinale* (10% - 20% cover).

QL122 Louisa Bridge (MC 85%)

This sample consists of 100% paludal tufa of intermediate strength. It is on level, unshaded ground, and the ground surface is mostly damp. Pools occupy 10% of the area and there is a small area of trickling water (3%) (Photo 3.26).

Graminoids cover 80% of the ground surface. The most abundant species are *Carex lepidocarpa, Festuca rubra* and *Molinia caerulea* (all ≥25% cover). Also present are *Carex panicea, C. flacca, C. dioica, Eleocharis quinqueflora, Juncus articulatus* and *J. inflexus*. Bryophytes are plentiful,

covering 65% of the surface. Most of this area is occupied by *Palustriella commutata* (40%), along with *P. falcata, Scorpidium cossonii, Campylium stellatum, Fissidens adianthoides, Bryum pseudotriquetrum, Aneura pinguis* and *Riccardia chamedryfolia*. Forbs occupy only 15% of the sample in total. They include *Anagallis tenella, Pinguicula vulgaris, Parnassia palustris* and *Succisa pratensis* (1% to 5% cover each). *Equisetum palustre* occupies 10% of the sample.

Four other samples recorded in this spring complex also belong to this group (MC 48% to 84%). All contain paludal tufa and some contain pools lined with marl. They are species-rich, with 30 or 31 species per sample. In addition to the above named species, they include *Samolus valerandi, Triglochin palustris, Crepis paludosa, Pulicaria dysenterica, Dactylorhiza incarnata, Briza media, Eriophorum angustifolium, Carex disticha, C. nigra* and *Plagiomnium elatum*.

QL124 Ballybannon (MC 93%)

Vegetation in this sample (see Photo 6.43) contains species typical of *Cratoneurion* communities but also some calcifuge species; *Erica tetralix* and *Drosera rotundifolia* are both present in small amounts (<1% cover). It is indicative of succession taking place, where, in the absence of grazing, a former wetland is drying out as dead vegetation accumulates and the living surface layer rises above the impact of mineral groundwater. No traces of tufa were found within this sample, although the vegetation is very close in composition to tufaceous samples and the membership coefficient indicates that this relevé is strongly associated with Group 6.

Bryophytes covered much of the surface beneath a mixed layer of vascular plants. *Calliergonella cuspidata* was the most abundant moss, along with *Palustriella commutata, Campylium stellatum, Scorpidium cossonii, Bryum pseudotriquetrum, Pellia endiviifolia* and *Aneura pinguis*. Graminoids were dominated by *Juncus articulatus, Carex flacca, C. panicea* and *Eriophorum angustifolium*, along with *C. lepidocarpa* and *Molinia caerulea*. Forbs included Succisa *pratensis, Anagallis tenella, Hydrocotyle vulgaris, Mentha aquatica* and *Triglochin palustris*.

The ground surface was mostly damp with pools occupying 5% of the sample area.

3.2.6f Syntaxonomy

Of my eight communities, Group 6 comes closest to the NVC M10 *Carex dioica-Pinguicula vulgaris* Mire community, which can be tufa forming (Rodwell 1998b). *Carex lepidocarpa* Small Sedge Springs also have affinities with M37 *Cratoneuron commutatum-Festuca rubra* springs and M38 *Cratoneuron commutatum-Carex nigra* springs. Of the small sedge communities described by Ó Críodáin & Doyle (1994), Group 6 samples come closest to the *Campylio-Caricetum dioicae* although my Group 6 vegetation is somewhat more calcicole in character.

3.2.7 *Palustriella falcata-Carex panicea* Springs

Group 7 *Palustriella falcata-Carex panicea* Springs are dominated by *Palustriella falcata* accompanied by small sedges, most notably *Carex panicea*. Several samples are from the Burren, where spring water issues over limestone pavement, forming thin stream crust tufa. The uncommon *Pinguicula grandiflora* abounds in some of these springs. Other samples, of wide geographic range, are on level or gently sloping, open sites and typically form paludal tufa of intermediate strength.

This group is moderately cohesive, containing 20 samples with a mean silhouette width of 0.08 (Fig. 3.3).

3.2.7a Floristics

Palustriella falcata, Carex panicea, C. lepidocarpa and *C. flacca* are constant and the first two of these species are highly significant indicators of the group (ISA***). There are three other significant indicator species: *Pinguicula grandiflora* (II), *Philonotis calcarea* (III) and *Briza media* (II).

P. falcata, present in 90% of samples, covers up to 75% of the ground surface, with a mean cover of 23% (Table 3.7). *P. commutata* is also frequent (III) but with lower cover values (mean 4%). The species occur jointly in 55% of Group 7 samples. (Where *P. falcata* occurs outside Group 7, its cover values are lower; it is frequent in Groups 5 and 8 (III in both, mean cover 1% and 5% respectively)). (See Fig. 3.5 for comparison of these species and also Table 3.10.)

Bryophytes occupy almost twice as much of the ground surface as graminoids (Fig. 3.4). As well as *Palustriella* species, *Philonotis calcarea, Bryum pseudotriquetrum* and *Aneura pinguis* are frequent, while *Breutelia chrysocoma, Campylium stellatum, Cratoneuron filicinum, Ctenidium molluscum, Fissidens adianthoides, Jungermannia atrovirens* and *Pellia endiviifolia* occur occasionally, sometimes with high cover values. The rare moss, *Catoscopium nigritum*, a Flora (Protection) Order species, occurs in one sample.

Graminoids comprise a diverse mix of species in which no one species is dominant. *Carex lepidocarpa, C. flacca and C. panicea* are ubiquitous (V), with mean cover values of 4% to 6%. Other graminoids include *Festuca rubra, Briza media, Sesleria caerulea, Molinia caerulea, Juncus articulatus, Eriophorum angustifolium* and *Schoenus nigricans*, with mean cover values ≤ 2%. *Eleocharis quinqueflora* is infrequent, but where it occurs (4 samples), it can be abundant (up to 10% cover).

Forbs are present in very small amounts; they include *Pinguicula grandiflora* (II), *P. vulgaris* (II) and *P. lusitanica* (I) as well as *Anagallis tenella, Parnassia palustris, Samolus valerandi, Potamogeton coloratus, Polygala vulgaris, Leontodon saxatilis, Linum catharticum, Bellis perennis* and *Prunella vulgaris* with mean cover values up to 2%.

Species diversity in this group is moderately high with a mean of 22 species per relevé (Fig. 3.9).

Table 3.7: Summary of statistically significant Indicator Species and other frequently occurring species in *Palustriella falcata-Carex panicea* Springs (Group 7).

ISA	Species	Frequency	Mean % Cover	Minimum % Cover	Maximum % Cover
***	*Palustriella falcata*	V	23	1	75
***	*Carex panicea*	V	6	0.5	40
***	*Pinguicula grandiflora*	II	0.3	0.1	3
**	*Philonotis calcarea*	III	4	0.1	40
**	*Briza media*	II	0.5	0.5	3
ns	*Hypericum tetrapterum*	II	<0.1	0.1	0.5
ns	*Equisetum variegatum*	I	1	20	20
ns	*Leontodon saxatilis*	I	0.2	1	3
	Carex lepidocarpa	V	5	0.5	15
	Carex flacca	V	4	0.5	10
	Agrostis stolonifera	IV	1	0.5	10
	Juncus articulatus	IV	1	0.5	3
	Bryum pseudotriquetrum	IV	1	0.1	2
	Palustriella commutata	III	4	1	20
	Festuca rubra	III	2	0.5	10
	Succisa pratensis	III	1	0.1	10
	Calliergonella cuspidata	III	1	0.1	5
	Aneura pinguis	III	1	0.1	2

3.2.7b Rare and Interesting Species

Pinguicula grandiflora

Pinguicula grandiflora occurs in five samples recorded from two localities in the Burren (Photo 3.31). In Ireland, this species is native only in the south-west; it is frequent in bogs and flushes in Counties Kerry and Cork (Parnell & Curtis 2012). Though initially regarded as a possible garden escape in the Burren, there is now no doubt but that it is native (Webb & Scannell 1983). Ireland represents the northern limit of its European distribution and it is absent from Britain (Heslop-Harrison 2004).

Lime-rich springs in the Burren are a departure from the more typical bog habitat, although associates of *P. grandiflora* in certain communities in Cork and Kerry, such as *Anagallis tenella, Carex panicea* and *C. lepidocarpa*, are indicative of a base-rich influence and the plant seems to tolerate a range of pH values as long as conditions are sufficiently wet or humid (Heslop-Harrison 2004).

In Group 7 samples, it occurs in the flush below springheads on bryophyte mats or shallow soils overlying limestone pavement or, where soils are deeper, on the damp sides of hummocks. The most frequent associates are *Palustriella falcata, P. commutata, Carex lepidocarpa, C. flacca* and *Succisa pratensis*.

Catoscopium nigritum

Catoscopium nigritum forms compact green cushions bearing distinctive sporophytes with shiny, globose, black capsules on a red seta (Photo 3.33). It occurs in one relevé, QL093 Dooaghtry, Co. Mayo (Photo 3.32). Here, it colonises a narrow band of very gently sloping damp ground, transitional between wetter flushed areas below and drier (low) mounds above. The vegetation consists of low-growing sedges, dominated by *Carex panicea* and stunted *Eleocharis quinqueflora,* and a carpet of mosses in which *Palustriella falcata* and *Philonotis calcarea* are conspicuous. The vegetation is closely cropped by grazing sheep.

Catoscopium nigritum is 'Near Threatened' in Ireland. It grows in dune slacks and damp machair along the west and north-west coast, in Counties Galway, Mayo and Donegal. While it is exclusively coastal in Ireland, in Britain and continental Europe it grows in mountain flushes, often on steep, rocky ground (Lockhart *et al.* 2012).

3.2.7c Environmental variables

Bare, unvegetated ground is characteristic of Group 7, occupying a greater proportion of the surface area (45%) than in any other group (although Group 8 comes close, Fig. 3.7). Bare limestone pavement in the Burren samples ranges from 15% to 50% of surface area in Group 7 samples (n=8). In addition, the proportion of dry ground is high, at 13% (Fig. 3.8); it occurs as small rocky islands around which the spring water flows (Photo 3.34) and is especially characteristic of Burren samples.

Stream crust tufa (mean cover 13%) is characteristic of the karst springs of the Burren, but paludal tufa is more abundant across the group as a whole (35% cover, Fig. 3.6). In most samples, the

strength of precipitation is intermediate, but it is occasionally heavily precipitated, and in three samples (15%) there is consolidated cascade tufa. Bare tufa is plentiful (28% cover, Fig. 3.7), often occurring as thin, stream crust tufa deposited over limestone pavement. Non-tufa surfaces are high (34% cover, Fig. 3.6). One sample, from Knocknagur, Co. Galway, lacks any trace of tufa even though the composition of its vegetation is very similar to other samples in this group (MC 90%).

Trickling water is plentiful, occurring in 60% of samples and occupying 16% of the ground surface (Fig. 3.8). Small pools are present in 80% of samples and occupy 11% of the overall area. All samples are unshaded, on level to gently sloping ground (mean slope 12°, Fig. 3.9).

3.2.7d Sample Locations

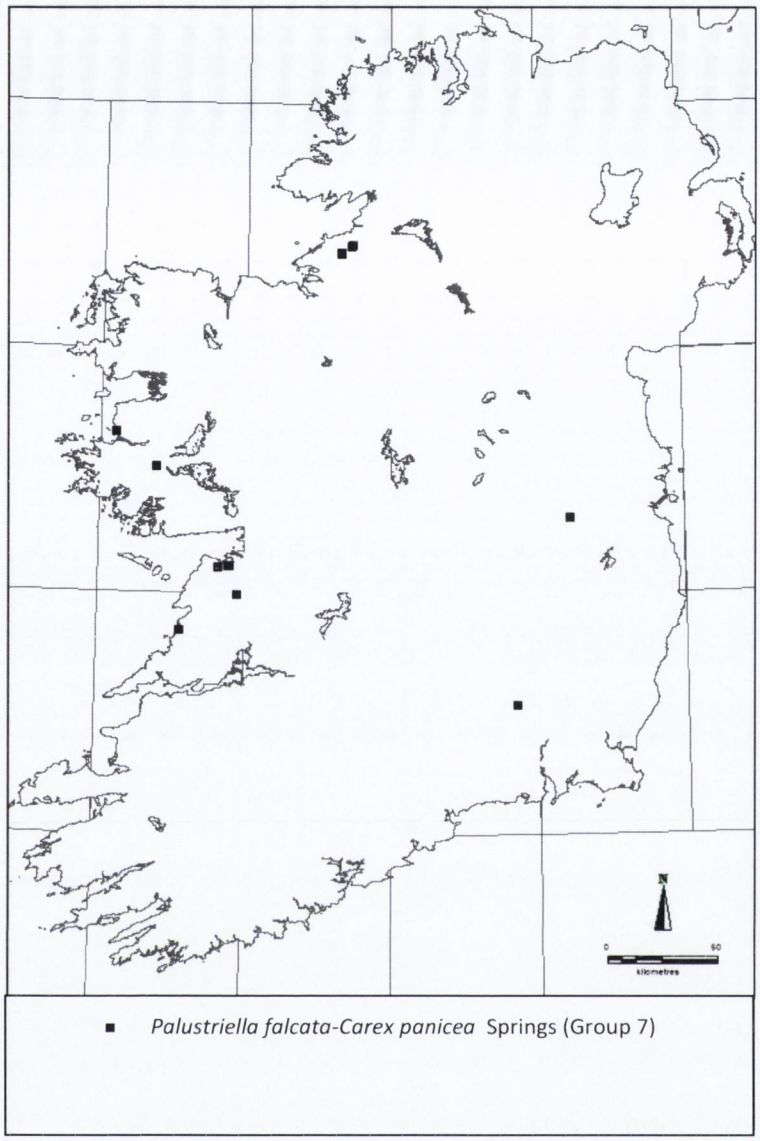
Group 7 samples are somewhat varied in the types of locations in which they occur. Their geographical distribution is shown on Map 3.7 (below). Eight samples (40%) were recorded on karst limestone in the Burren: these are mostly from the north Burren, on Cappanawalla above Newtown (3 samples) and on Moneen Mountain, at Glennamanagh (3 samples) and above Acres Village (1 sample). One sample is from the south-east Burren, near Rinnamona Lough. Seventeen Burren samples were recorded in total for this project and they are widely spread across the groups (one or more in each group, except Group 2). Group 7 Burren samples are all on flushed limestone pavement while samples in other groups mostly occur in fens and waterfalls.

Five samples (25%) are from the Glenade area of Co. Leitrim: four are from springheads and flushes in fields at the foot of Tievebaun and Arroo Mountains (altitude 180 – 185m); one is a more upland flush below the north-facing cliffs of Arroo Mt (altitude 275m). Three samples (15%) are from Thomastown Quarry in Co. Kilkenny; in this long-abandoned quarry, springs well up to form shallow, seasonal pools and a small area of fen. The remainder constitutes a mixed group from various locations: Ballynafagh (Co. Kildare), Dooaghtry (Co. Mayo), Knocknagur (Co. Galway) and Spanish Point (Co. Clare).

3.2.7e Typical samples

QL075 Moneen, Burren (MC 78%)

This sample is typical of Burren springs containing *Pinguicula grandiflora*. Half of the surface area is dry, bare limestone. The other half consists of weakly-formed paludal tufa and thin, stream crust tufa in equal measure. Water trickles over a quarter of the surface and the mean slope is 5° (Photo 3.34).



Map 3.7: Locations of *Palustriella falcata-Carex panicea* Spring relevés (Group 7; n=20). See Appendix II for list of samples.

The area of paludal tufa is vegetated. *Palustriella falcata* is the most abundant species (15% cover) followed by *Carex lepidocarpa, C. flacca, Pinguicula grandiflora* and *Bellis perennis*. Small amounts (up to 1% cover) of *P. commutata, Bryum pseudotriquetrum, Calliergonella cuspidata* and *Aneura pinguis* are present.

Palustriella falcata thrives along the edges of bare, flushed rock, stretching its shoots out horizontally over the rock surface (Photo 3.35). Eventually, it forms a thin mat on which other species (especially small sedges and sometimes *Pinguicula grandiflora*) can become established (Photo 3.31).

QL198 Glenade Cascade (MC 97%)

Here, a heavily petrified spring emerges on the lower slopes of Tievebaun Mt at the eastern end of the Benbulbin Range. The mean slope is 25°. It comprises cascade tufa, oncoids/ooids and strongly precipitated paludal tufa (Photo 3.36). 55% of the surface is bare, unvegetated tufa. Water trickles over 20% of the surface, pools cover 10% and the remainder is damp.

Palustriella falcata covers 15% of the surface, along with *Eleocharis quinqueflora, Carex lepidocarpa, C. flacca* and *C. panicea* (2% to 10% cover). There are smaller quantities of *Pinguicula vulgaris, Anagallis tenella, Parnassia palustris, Carex dioica, C. pulicaris, Eriophorum angustifolium, Selaginella selaginoides, Hymenostylium recurvirostrum* var. *recurvirostrum, Campylium stellatum, Breutelia chrysocoma, Jungermannia atrovirens, Aneura pinguis* and *Pellia endiviifolia*.

QL168 Thomastown Quarry (MC 95%)

During the winter, water covers the quarry floor at this location to a depth of a few centimetres. In May 2013, when the relevé was recorded, the ground was damp without obvious surface water (Photo 3.37). By September 2013, following an unusually dry summer, it had dried out completely. The sample is unusual in this respect since almost all of the relevés recorded for this project remain irrigated throughout the year.

The relevé consists of a combination of vegetated paludal tufa and bare marl. *Palustriella commutata* and *P. falcata* are present in approximately equal amounts, together occupying 60% of the ground surface. *Carex panicea* is abundant, along with smaller amounts of *Succisa pratensis, Triglochin palustris, Tussilago farfara, Briza media, Festuca rubra, Carex lepidocarpa, C. flacca, Fissidens adianthoides, Campylium stellatum* and *Aneura pinguis*.

3.2.7f Synataxonomy

Ivimey-Cook & Proctor's Calcareous Spring Communities of the Burren (1966) correspond closely with my Group 7 samples except that, in the former, *Cratoneuron filicinum* and *Pellia endiviifolia* replace *Palustriella falcata* and *P. commutata* as constants and *Carex lepidocarpa* and *C. panicea* are less frequent. Turfy Marshes in Upper Teesdale (Pigott 1956) show a remarkably similar floristic composition to Group 7 and their physiognomy, though different, perhaps parallels Burren samples; the vegetated hummocks of Upper Teesdale's Turfy Marshes are separated by calcareous gravel rather than by limestone pavement as in the Burren.

3.2.8 *Saxifraga aizoides-Seligeria oelandica* Springs

Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs are exceptionally species-rich, characterised by *Saxifraga aizoides* and a suite of rare bryophyte species. Vegetation nestles in rock crevices and clings to steep, flushed cliffs (Photo 3.38). Thin stream crust tufa forms over exposed bedrock. Samples are centred on the Benbulbin Range, west Fermanagh and north-east Antrim.

This group is one of the most strongly cohesive with a mean silhouette width of 0.17 (Fig. 3.3). It is the smallest group, with 13 samples from eight sites.

3.2.8a Floristics

Saxifraga aizoides and *Festuca rubra* are constant (V Table 3.8 below) and are very highly significant indicators of the group (ISA***). The rare bryophytes *Seligeria oelandica, S. patula, Orthothecium rufescens* and *Hymenostylium recurvirostrum* var. *insigne* are frequent and characteristic components of this vegetation (constancy class III); they are all very highly significant indicators of Group 8 (ISA***).

These rare species are accompanied by a diverse range of more familiar plants. Most often, *Sesleria caerulea, Carex flacca, Palustriella commutata, Breutelia chrysocoma, Bryum pseudotriquetrum, Jungermannia atrovirens, Aneura pinguis* and *Pellia endiviifolia* are present (constancy class IV or V). Other frequent associates include *Parnassia palustris, Pinguicula vulgaris, Succisa pratensis, Bellis perennis, Prunella vulgaris, Campanula rotundifolia, Fissidens adianthoides* and *Palustriella falcata* (constancy class III).

Gymnostomum aeruginosum and *Hymenostylium recurvirostrum* var. *recurvirostrum* are occasionally present and are highly significant group indicators (ISA***). Occasional species also include *Tussilago farfara, Alchemilla glabra, Primula vulgaris, Deschampsia cespitosa, Selaginella selaginoides, Philonotis calcarea, Leiocolea collaris* and *Preissia quadrata*. There is one non-native species, *Epilobium brunnescens*, present in small amounts (constancy class II, mean cover 0.1%).

This group has the greatest diversity of species and the highest number of statistically significant species. The mean number of species per sample is 34 (Fig. 3.9), with a range of 21 to 49. Eighteen species are very highly significant group indicators (ISA ***) and a further 19 are significant at ISA ** or *. In tandem with the high number of species, cover values of individual species are low. Seldom does any species exceed 10% cover and the only species to reach this value frequently is *Festuca rubra*.

Table 3.8: Summary of statistically significant Indicator Species and other frequently occurring species in *Saxifraga aizoides-Seligeria oelandica* Springs (Group 8).

ISA	Species	Frequency	Mean % Cover	Minimum % Cover	Maximum % Cover
***	*Festuca rubra*	V	8	2	15
***	*Saxifraga aizoides*	V	4	0.5	15
***	*Sesleria caerulea*	IV	5	1	15
***	*Aneura pinguis*	IV	1	0.1	5
***	*Jungermannia atrovirens*	IV	1	0.1	5
***	*Linum catharticum*	IV	0.1	0.1	0.5
***	*Hymenostylium insigne*	III	1	0.1	5
***	*Orthothecium rufescens*	III	1	0.1	5
***	*Seligeria oelandica*	III	1	0.5	5
***	*Seligeria patula*	III	1	0.1	5
***	*Prunella vulgaris*	III	0.4	0.1	2
***	*Campanula rotundifolia*	III	0.3	0.1	2
***	*Bellis perennis*	III	0.2	0.1	1
***	*Dicranella varia*	III	0.1	0.1	0.5
***	*Hymenostylium recurvirostrum*	II	0.4	0.1	3
***	*Alchemilla glabra*	II	0.2	0.1	1
***	*Gymnostomum aeruginosum*	II	0.1	0.1	1
***	*Scorzoneroides autumnalis*	II	0.1	0.1	0.5
**	*Carex flacca*	V	6	0.5	20
**	*Cirsium palustre*	IV	1	0.1	2
**	*Taraxacum officinale* agg.	IV	0.3	0.1	2
**	*Fissidens adianthoides*	III	0.3	0.1	1
**	*Parnassia palustris*	III	0.2	0.1	1
**	*Tussilago farfara*	II	1	0.5	5
**	*Primula vulgaris*	II	0.2	0.5	1
**	*Epilobium brunnescens*	II	0.1	0.1	0.5
**	*Rhytidiadelphus squarrosus*	II	0.1	0.1	0.5
**	*Rhytidiadelphus triquetrus*	II	<0.1	0.1	0.1
**	*Pohlia wahlenbergii*	II	<0.1	0.1	0.2
*	*Breutelia chrysocoma*	IV	1	0.1	4
*	*Pinguicula vulgaris*	III	0.4	0.5	2
*	*Deschampsia cespitosa*	II	0.4	0.5	3
*	*Riccardia chamedryfolia*	II	0.2	0.1	2
*	*Thuidium tamariscinum*	II	0.1	0.1	0.5
*	*Trichostomum crispulum*	II	0.1	0.1	0.5
*	***Leiocolea collaris***	I	**0.1**	**0.1**	**1**
*	***Leiocolea turbinata***	I	**<0.1**	**0.1**	**0.2**
ns	***Preissia quadrata***	I	**0.2**	**0.1**	**2**
	Pellia endiviifolia	V	3	0.1	10
	Agrostis stolonifera	V	2	0.5	10
	Palustriella commutata	IV	5	0.1	15
	Juncus articulatus	IV	2	0.1	10
	Ctenidium molluscum	IV	2	0.5	10
	Calliergonella cuspidata	IV	2	0.1	10
	Bryum pseudotriquetrum	IV	1	0.1	5
	Palustriella falcata	III	5	0.5	40
	Succisa pratensis	III	1	0.5	3

Living vegetation covers 50% of the area sampled and leaf litter/standing dead material is sparse with 6% cover (Fig. 3.7). Bryophytes occupy the greatest proportion of the vegetated area, but their cover is almost matched by graminoids, while forbs amount to only one third of the area of bryophyte cover (Fig. 3.4).

3.2.8b Rare Species

Saxifraga aizoides

Saxifraga aizoides (Photo 3.39 and 3.41) is a rare plant in Ireland, occurring only in the north-west (Sligo, west Leitrim, west Fermanagh and south Donegal) and in Co. Antrim (BSBI website, accessed 10th November 2014). In Group 8, it is present in all the Benbulbin Range samples, both Fermanagh samples and also in two samples recorded at Murlough Bay, on the north-east coast of Co. Antrim.

Seligeria oelandica

Seligeria oelandica colonises steep, flushed rock surfaces in samples from the Benbulbin Range and Fermanagh. Its tiny shoots, a few millimetres tall, bear pointed black leaves and barely protrude above the tufa film in which they grow (Photo 3.40). Sporophytes are usually present; these are distinctive, with a stout seta and reddish, wide-mouthed, turbinate capsules. The species occurs in only three vice-counties in Ireland – Sligo, Leitrim and Fermanagh – with most populations situated on the Benbulbin Range. Its status in Ireland is 'Vulnerable' (Lockhart *et al.* 2012). It has a single station in Britain, in the south of Wales (Bosanquet & Motley 2009), and a disjunct distribution worldwide. In continental Europe, it occurs in Spitsbergen, Norway, Sweden, Switzerland and in the Western Carpathians (Ochyra 1991); in most of these locations it is declining or vulnerable. It is also known in NE Asia and northern N. America. It is vulnerable to physical disturbance by livestock or walkers, to shading if overgrown by taller vegetation and to changes in the flow or quality of water (Lockhart *et al.* 2012).

Seligeria patula

Seligeria patula (III, ISA ***) often grows in close proximity to *S. oelandica* and was present in most Benbulbin Range samples. It is similar in size to *S. oelandica* but differs in its distinctive, three-ranked arrangement of leaves. The status of *S. patula* in Ireland is 'Near Threatened'. There are recent records from three vice-counties (Sligo, Leitrim and Fermanagh), where large populations are present (Lockhart *et al.* 2012). This species is endemic to Europe.

Orthothecium rufescens

Orthothecium rufescens (III, ISA ***) is present in most Benbulbin Range samples and one sample from the Burren. A striking pleurocarp, it has long, metallic pinkish-red shoots which form silky wefts in rock crevices and at the edges of grassy vegetation (Photo 3.41). Its main centre of population is in the Benbulbin Range but it is also reported from Fermanagh and west Donegal. The Burren (at Black Head) is its only station outside of the north-west. It is 'Near Threatened' in Ireland (Lockhart *et al.* 2012). It is common in parts of the Scottish Highlands on base-rich ground (Porley & Hodgetts 2005).

Hymenostylium recurvirostrum var. *insigne*

Hymenostylium recurvirostrum var. *insigne* (III, ISA ***) is present in most of the Benbulbin Range samples, where luxuriant cushions drape dripping rocks (Photo 3.42). It is not known in Ireland outside of this locality and its status in Ireland is 'Near Threatened'. It is rare in Europe, occurring only in NW Scotland and at a few localities in Spain. Irish specimens are distinct from the smaller var. *recurvirostrum*; elsewhere, plants with intermediate morphological characteristics have been found, hence the ranking at variety rather than species level (Lockhart *et al.* 2012). Formerly regarded as endemic to Western Europe, this variety is now known at disjunct localities in western N. America, S. America and China.

3.2.8c Environmental Variables

These samples are, on the whole, more upland than other groups (Fig. 3.9). The mean altitude is 243m (the other group means range from 65m to 125m). Most Group 8 samples are above 170m, the highest being 369m (Tievebaun Mt). Two samples close to the coast (Black Head, Co. Clare and Howth, Co. Dublin) have low altitudes (62m and 32m respectively).

These are steeply inclined sites with a mean slope of 53°, second only to Group 1 (Fig. 3.9). The predominant form of tufa is stream crust tufa (Fig. 3.6) and it is much more prevalent here than in any other group, with a mean cover of 33% - more than twice that of the nearest group (Group 7, mean cover 13%). Cascade tufa is mostly absent but, in one sample (at Murlough Bay, Photo 3.46), it is the dominant form. Paludal tufa, weak to intermediate in strength, is present in most samples (77% frequency, mean cover 18%) but, on the whole, it is less prevalent in Group 8 than in Groups 5, 6 and 7. Non-tufa cover values are moderately high, occupying 40% of the ground surface.

Bare tufa is plentiful at 27% of surface area (Fig. 3.7). This occurs as flushed, stream crust tufa and, while devoid of vascular plants and bryophytes, it is almost always associated with a thin algal film. Bare stone amounts to 13% of the area sampled, second only to Group 7.

Most of the ground surface is damp (74%, Fig. 3.8), but dripping water is present in 62% of samples (mean area irrigated by dripping water is 12%). Trickling water occupies, on average, 8% of the ground surface and 5% is dry. Pools are absent from these steep locations.

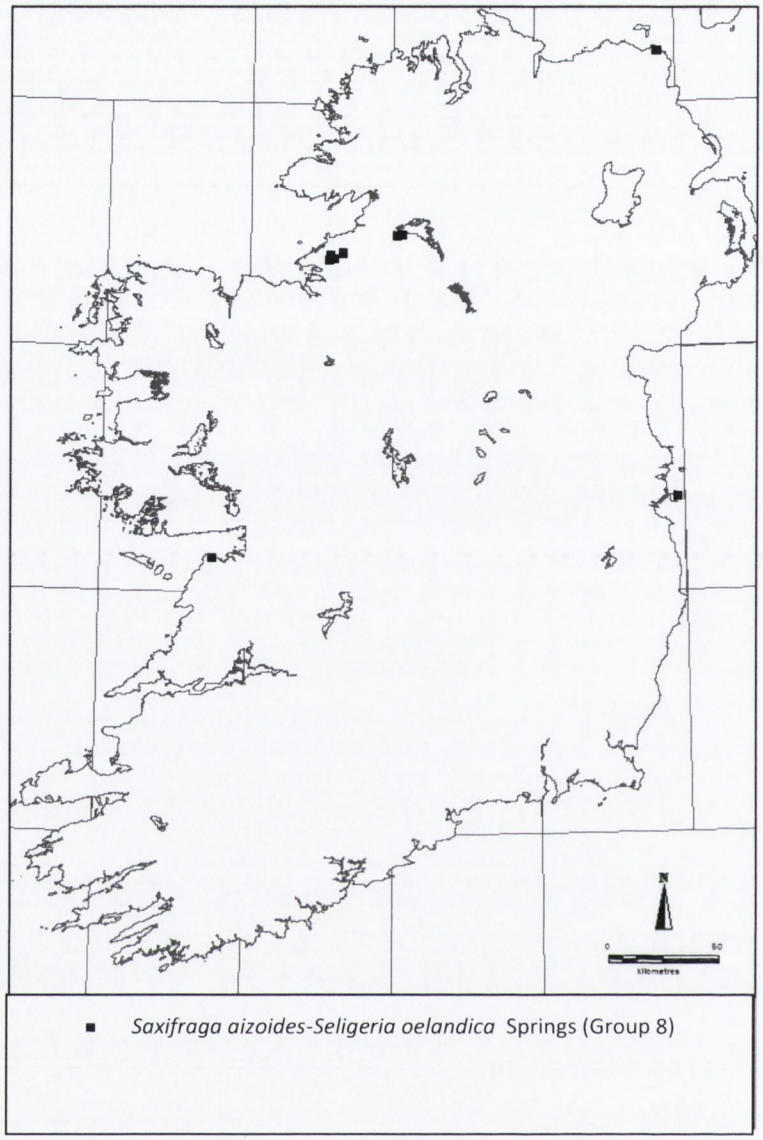
Canopy cover is absent in all samples (apart from one which is lightly shaded by a stunted ash tree perched on the cliff above) but the northerly aspect of most samples moderates summer temperature and insolation. Two samples, including the lightly shaded relevé, face approximately east (70 – 110°); the remainder (85%) face in more northerly directions, between 300° (approx. NW) and 60° (approx. NE).

3.2.8d Sample Locations

Seven samples (54%) are located on the Benbulbin Range, along the northern fringes, extending from Benbulbin eastwards to Benwiskin, Gleniff and Eagle's Rock on Tievebaun Mountain (Map 3.8). These are exceptionally species-rich localities (*e.g.* Praeger 1934, Lockhart *et al.* 2012); all of the rare species described above are constant (classes V and IV). These samples are all strongly associated with Group 8 (Membership Coefficients 97% - 99%).

Two samples (15%) are on the north-facing Cliffs of Magho in west Fermanagh (MC 91% and 83%), 30km east-north-east of Benbulbin. The ecology of this area is reminiscent of the Benbulbin Range; *Saxifraga aizoides* is locally abundant on flushed limestone cliffs and *Seligeria oelandica* has its only Irish station outside of Sligo/Leitrim. Two samples are from Murlough Bay, Co. Antrim (MC 82% and 51%). These contain plentiful *Saxifraga aizoides* but none of the rare species of bryophytes. One sample is from Black Head, Co. Clare (MC 89%, Photo 3.44) and contains *Orthothecium rufescens*. (The species was recorded in crevices in this locality by Ivimey-Cook and Proctor (1966) in a relevé assigned to *Adiantum capillus-veneris* Stands).

One anomalous sample, from QL166 Kilrock Quarry, Howth, Co. Dublin, is weakly associated with Group 8 (MC 48%). It shares with other Group 8 samples only the more generalist species such as *Linum catharticum, Prunella vulgaris, Bellis perennis, Festuca rubra, Aneura pinguis* and *Riccardia chamedryfolia*. This sample is intermediate between Group 8, Group 6 (MC 24%) and Group 4 (MC 16%).



Map 3.8: Locations of *Saxifraga aizoides-Seligeria oelandica* Spring relevés (Group 8; n=13). See Appendix II for list of samples.

3.2.8e Typical Samples

QL135 Benbulbin (MC 99%)

This is one of the most species-rich relevés (Photo 3.43). It contains all the rarities of the group: *Saxifraga aizoides* (3% cover), *Seligeria oelandica* (5%), *S. patula* (0.2%), *Orthothecium rufescens* (3%) and *Hymenostylium recurvirostrum* var. *insigne* (2%). In total 43 species are present; these include *Pinguicula vulgaris, Lysimachia nemorum, Tussilago farfara, Alchemilla glabra, Scorzoneroides autumnalis, Bellis perennis, Festuca rubra, Sesleria caerulea, Deschampsia cespitosa, Carex lepidocarpa, C. panicea, C. lepidocarpa, Palustriella commutata, Hymenostylium*

recurvirostrum var. *recurvirostrum, Gymnostomum aeruginosum, Pohlia wahlenbergii, Jungermannia atrovirens, Leiocolea turbinata, Aneura pinguis* and *Pellia endiviifolia*.

This high number of species is present in spite of the fact that 43% of the sample area is unvegetated (35% of the surface is bare tufa and 5% bare stone). Graminoids cover 25% of the quadrat, bryophytes 24% and forbs 10%.

Tufa is present in 90% of the sample area, predominantly in the form of stream crust tufa (55%) but with some paludal tufa (intermediate strength) and a small tufa cascade. Most of the surface is damp (85%), with a little trickling and dripping water.

This relevé is at an altitude of 324m, faces NNW and is inclined at 60°.

QL211 Murlough Bay (MC 82%)

This seepage contains *Saxifraga aizoides* but lacks the rare bryophytes of Benbulbin. The laterite clays of north Antrim lend to it a very different appearance (Photo 3.45). Unlike the sparsely vegetated, rocky surface of Benbulbin samples, vegetation cover here is almost continuous on deeper soils. Where slumping or sheep tracks expose the soil, the strong red colour contrasts vividly with the vegetation.

This sample is weakly tufaceous, with just a trace of paludal tufa, and the vegetation is dominated by *Cratoneuron filicinum* (60% cover) along with *Carex flacca* (20%) and *Calliergonella cuspidata* (10%). Also present in smaller amounts are *Saxifraga aizoides, Pinguicula vulgaris, Festuca rubra, Palustriella falcata, Pellia endiviifolia* and *Aneura pinguis*.

Much more strongly tufa-forming (though less closely associated with Group 8, MC51%) is a nearby sample, QL208 Murlough Bay (Photo 3.46). It contains *Palustriella falcata* (40% cover), *P. commutata* (15%), *Saxifraga aizoides* and *Festuca rubra* (10% cover), growing on a tufa cascade. Also present are *Parnassia palustris, Primula vulgaris, Carex flacca* and *Aneura pinguis*.

These samples face north-east on slopes inclined at 50°.

3.2.8f Syntaxonomy

The presence of *Saxifraga aizoides* links this group to a number of described communities. The strongest affinities are with British *Saxifragetum aizoidis* communities (*e.g.* U15 Rodwell 1998c), in which *S. aizoides* and *Festuca rubra* are constant and there is a broad overlap in general species composition. The species *Seligeria oelandica* and *Saxifraga aizoides* were jointly recorded in a high-altitude community in Norway (Coker 1983), but there are few other species in common with Group 8 on account of the very different biogeographical setting. *Saxifraga aizoides* and *Palustriella falcata* are indicative of Alpine *Cratoneuretum falcati* communities (*e.g.* Braun-Blanquet 1978), although, of course, characteristic species of the alpine community such as *Arabis soyeri* ssp. *subcoriacea* and *Aster bellidiastrum* are absent from Ireland.

3.2.9 Tables and Figures relating to plant communities

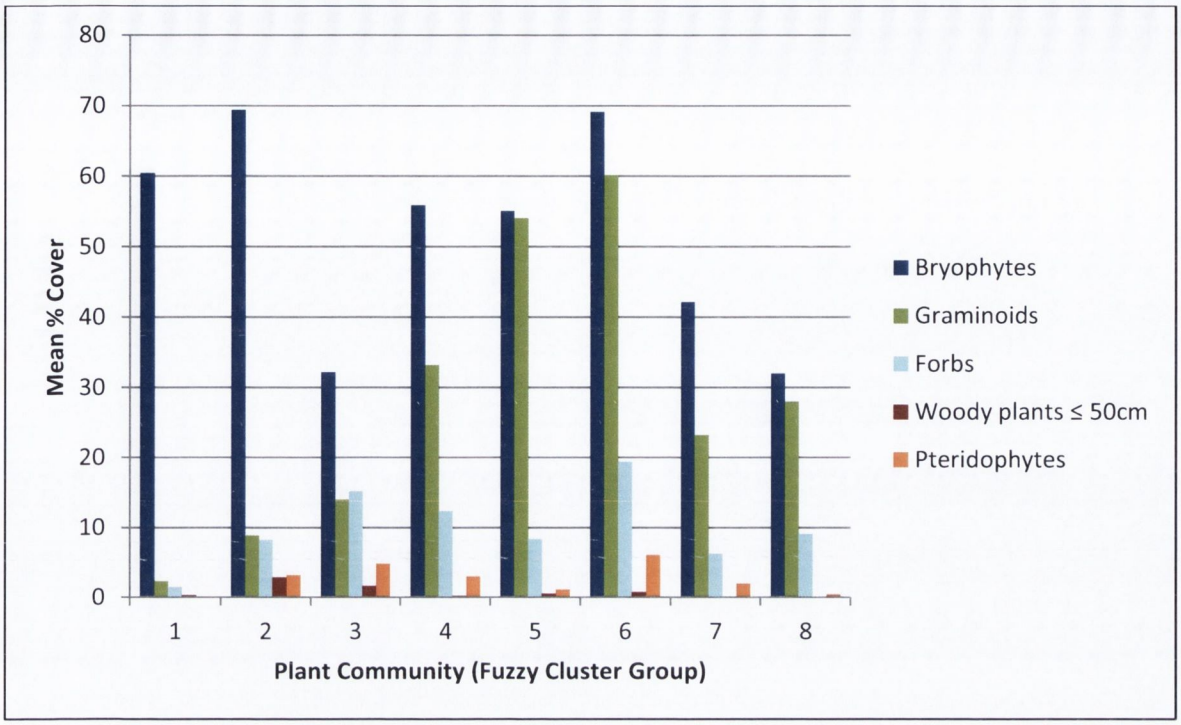


Fig. 3.4: Ground cover by plant groups in fuzzy cluster groups. (Totals may exceed 100% owing to overlap of layers in the vegetation. See App. IV for data.)

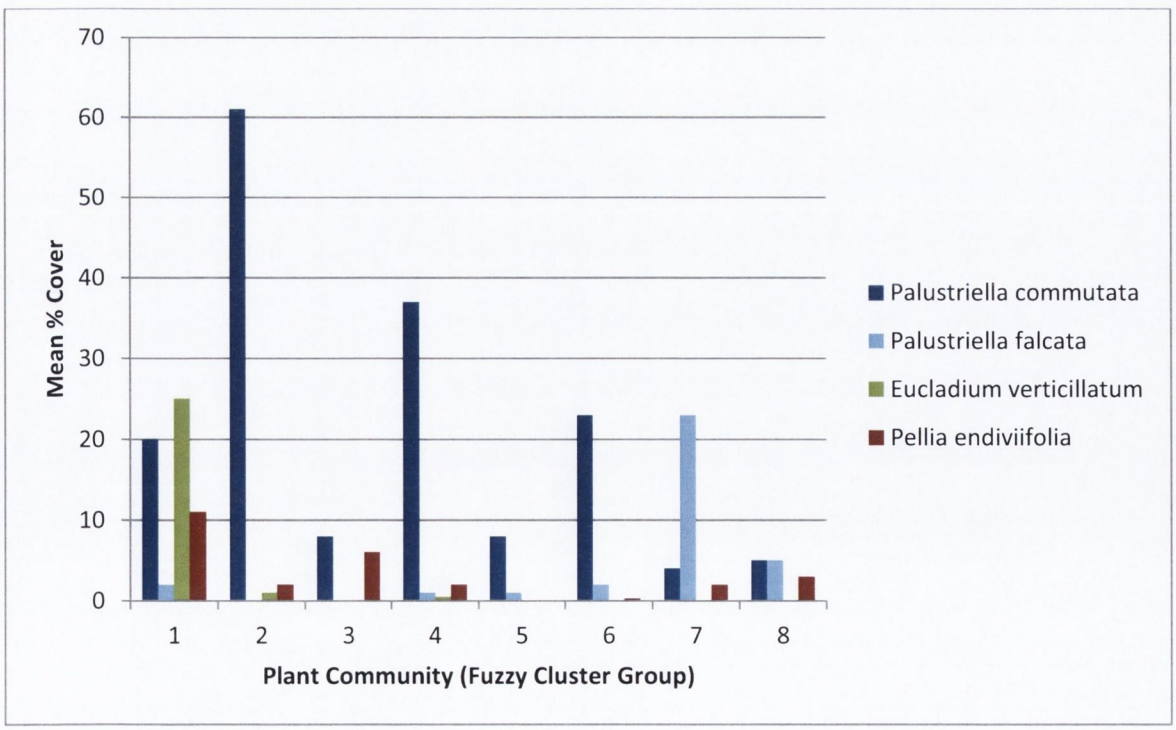


Fig. 3.5: Relative abundance of four leading bryophyte species in fuzzy cluster groups

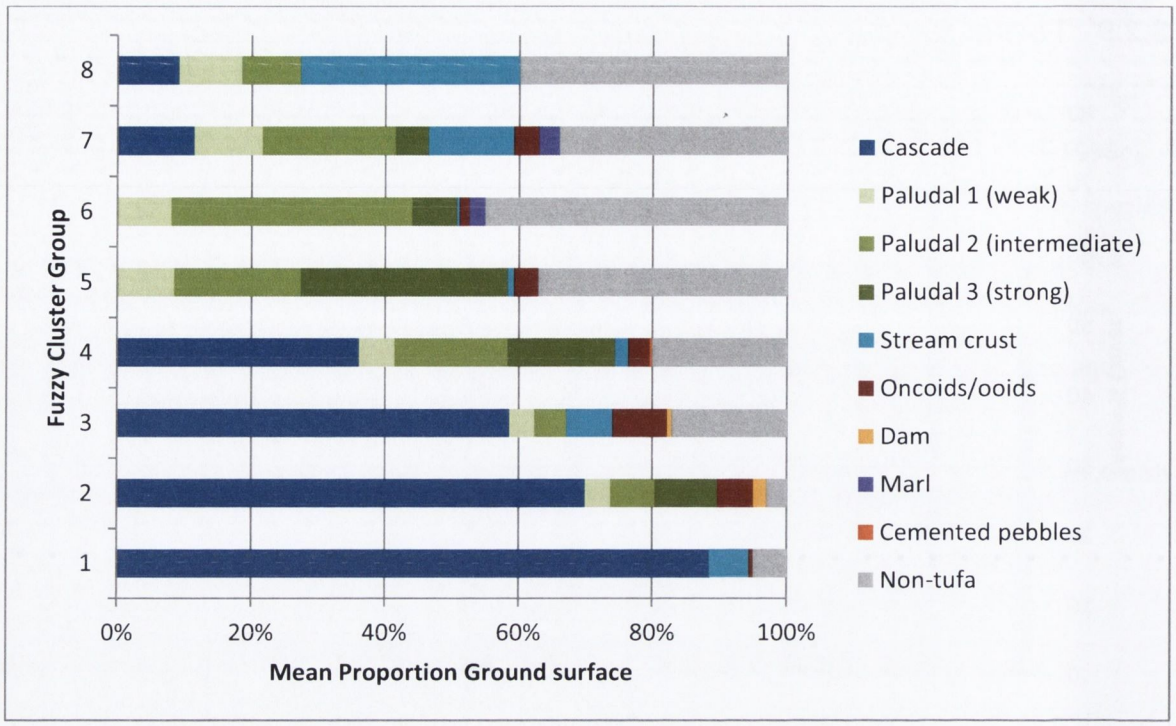


Fig. 3.6: Tufa formation type in fuzzy cluster groups. (See App. IV for data.)

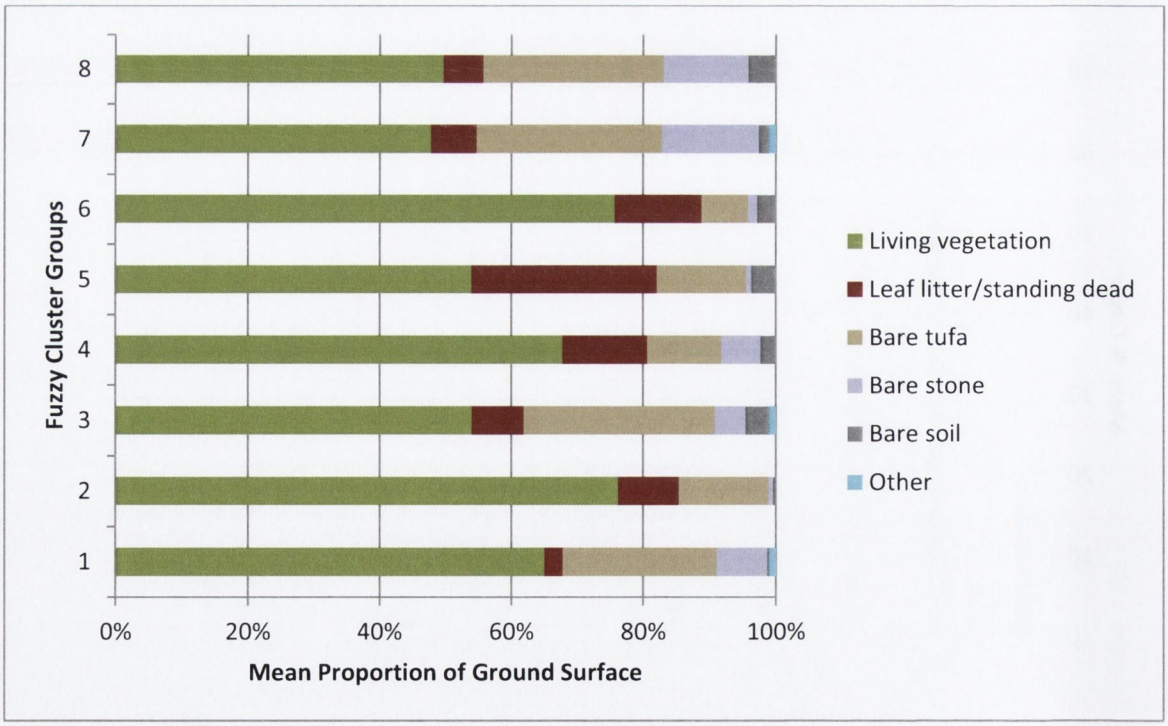


Fig. 3.7: Surface composition in fuzzy cluster groups. (See App. IV for data.)

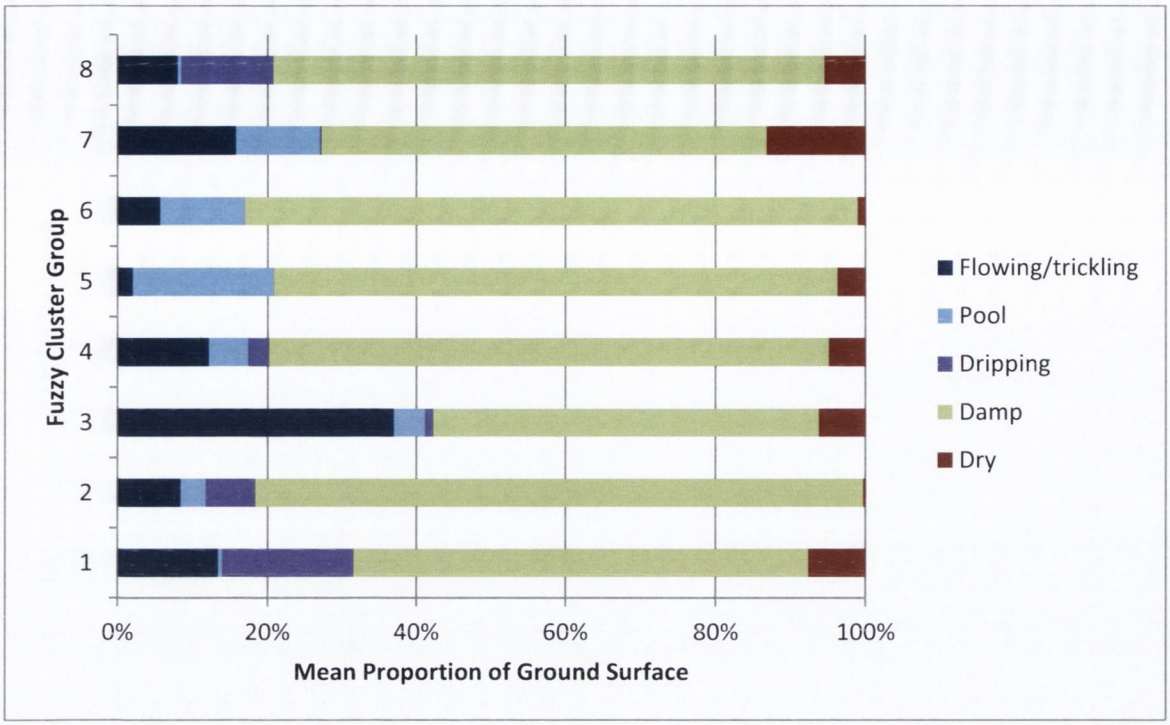


Fig. 3.8: Surface water in fuzzy cluster groups. (See App. IV for data.)

Table 3.9: General attributes of plant communities (see also boxplots, Fig. 3.9). For other attributes, see App. IV.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Number of samples (n)	18	26	29	28	22	30	20	13
Mean silhouette width	0.20	0.16	-0.01	0.04	0.17	0.09	0.08	0.17
Mean no. species / $4m^2$ relevé	8.7	14.1	13.8	19.7	21.7	26.8	22.1	33.8
Mean altitude (m)	89	125	114	117	65	71	112	243
Mean slope ($^{\circ}$)	70	36	27	26	5	5	12	53
Mean canopy cover (%)	33	51	50	9	0	0	0	1

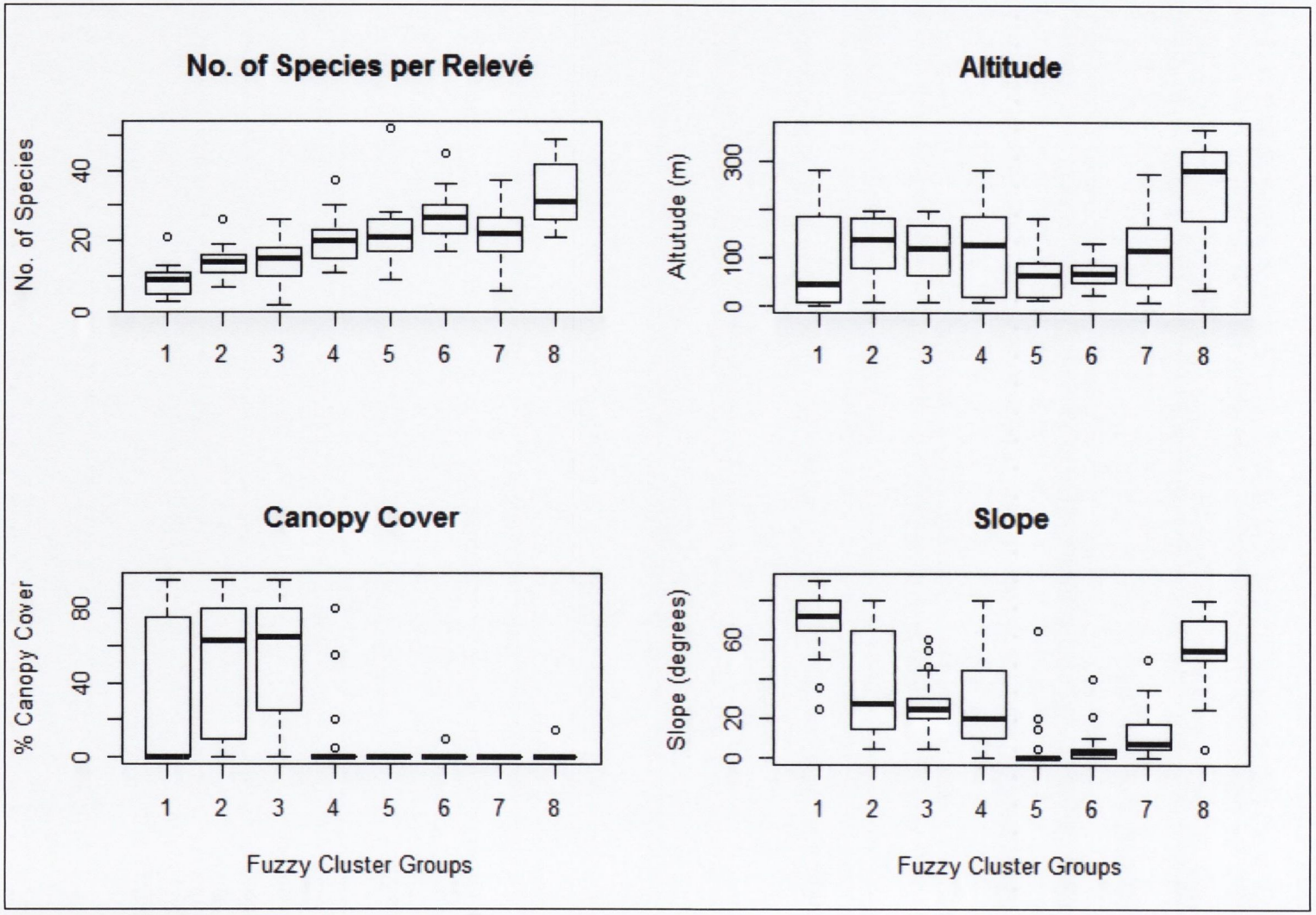


Fig. 3.9: General attributes of plant communities (Fuzzy Cluster Groups). (Boxplots depict median and range; see Table 3.9 above for mean values.)

Table 3.10: Top twenty species in fuzzy cluster groups (by mean % cover)

Group 1: *E.ver-P.end Tufa Casc.*	%
Eucladium verticillatum	24.6
Palustriella commutata	20.4
Pellia endiviifolia	11.3
Didymodon tophaceus	2.5
Palustriella falcata	1.7
Plantago maritima	0.9
Festuca rubra	0.6
Conocephalum conicum agg.	0.6
Agrostis stolonifera	0.6
Sesleria caerulea	0.6
Cratoneuron filicinum	0.5
Geranium robertianum	0.3
Hedera helix	0.3
Thamnobryum alopecurum	0.2
Tussilago farfara	0.2
Brachythecium rivulare	0.2
Carex distans	0.2
Schoenus nigricans	0.2
Breutelia chrysocoma	0.2
Brachypodium sylvaticum	0.1

Group 2: *P.com-G.riv* Springheads	%
Palustriella commutata	60.6
Geranium robertianum	4.3
Agrostis stolonifera	3.4
Equisetum telmateia	2.3
Conocephalum conicum agg.	2.2
Pellia endiviifolia	1.9
Rubus fruticosus	1.7
Cratoneuron filicinum	1.5
Carex remota	1.5
Ranunculus repens	1.4
Eucladium verticillatum	1.2
Juncus inflexus	1.0
Chrysosplenium oppositifolium	1.0
Brachythecium rivulare	1.0
Eupatorium cannabinum	0.8
Asplenium scolopendrium	0.8
Thamnobryum alopecurum	0.7
Hedera helix	0.7
Carex flacca	0.7
Brachypodium sylvaticum	0.6

Group 3: *B.riv-P.rip* Streams & Fl.	%
Palustriella commutata	8.1
Pellia endiviifolia	6.1
Platyhypnidium riparioides	5.7
Cratoneuron filicinum	5.4
Nasturtium officinale agg.	5.3
Agrostis stolonifera	4.9
Equisetum telmateia	4.6
Holcus lanatus	4.0
Brachythecium rivulare	3.6
Ranunculus repens	3.1
Carex remota	2.8
Bryum pseudotriquetrum	1.7
Geranium robertianum	1.4
Mentha aquatica	1.3
Glyceria notata	1.3
Plagiomnium undulatum	1.1
Apium nodiflorum	1.0
Brachypodium sylvaticum	0.9
Didymodon tophaceus	0.7
Deschampsia cespitosa	0.7

Gr. 4: *P.com-A.stol* Springheads	%
Palustriella commutata	37.3
Festuca rubra	10.3
Carex flacca	8.1
Calliergonella cuspidata	5.7
Eupatorium cannabinum	3.6
Agrostis stolonifera	3.5
Juncus articulatus	2.8
Cratoneuron filicinum	2.7
Carex lepidocarpa	2.4
Bryum pseudotriquetrum	2.1
Equisetum telmateia	2.1
Brachythecium rivulare	1.9
Pellia endiviifolia	1.9
Schoenus nigricans	1.9
Juncus inflexus	1.5
Mentha aquatica	1.5
Deschampsia cespitosa	1.4
Filipendula ulmaria	1.4
Schedonorus arundinaceus	1.2
Lophocolea bidentata	1.2

Group 5: *Schoenus* Springs	%
Schoenus nigricans	35.5
Campylium stellatum	21.5
Scorpidium scorpioides	10.0
Molinia caerulea	9.4
Palustriella commutata	8.0
Scorpidium cossonii	5.1
Breutelia chrysocoma	5.0
Ctenidium molluscum	4.3
Carex lepidocarpa	2.9
Festuca rubra	2.8
Menyanthes trifoliata	2.0
Chara vulgaris	1.6
Succisa pratensis	1.6
Carex flacca	1.5
Carex panicea	1.4
Eleocharis quinqueflora	1.4
Calliergonella cuspidata	1.4
Juncus subnodulosus	1.4
Palustriella falcata	1.2
Philonotis calcarea	1.0

Group 6: *C.lep* Small Sedge Springs	%
Calliergonella cuspidata	23.3
Palustriella commutata	22.5
Carex lepidocarpa	11.5
Festuca rubra	8.5
Molinia caerulea	7.6
Carex flacca	7.5
Juncus subnodulosus	7.1
Campylium stellatum	6.4
Cratoneuron filicinum	6.2
Juncus articulatus	5.0
Succisa pratensis	4.6
Carex panicea	4.6
Scorpidium cossonii	3.4
Carex rostrata	3.3
Equisetum palustre	2.5
Anagallis tenella	2.5
Schoenus nigricans	2.4
Menyanthes trifoliata	2.3
Equisetum fluviatile	2.2
Agrostis stolonifera	2.1

Group 7: *P.fal-C.pan* Springs	%
Palustriella falcata	23.3
Carex panicea	5.7
Carex lepidocarpa	5.5
Campylium stellatum	4.6
Palustriella commutata	4.2
Philonotis calcarea	3.7
Carex flacca	3.6
Anagallis tenella	1.8
Eleocharis quinqueflora	1.8
Pellia endiviifolia	1.6
Festuca rubra	1.6
Cratoneuron filicinum	1.5
Agrostis stolonifera	1.3
Succisa pratensis	1.0
Carex rostrata	1.0
Ctenidium molluscum	1.0
Equisetum variegatum	1.0
Eriophorum angustifolium	1.0
Breutelia chrysocoma	0.8
Fissidens adianthoides	0.8

Group 8: *S.aiz-S.oel* Springs	%
Festuca rubra	7.9
Cratoneuron filicinum	7.7
Carex flacca	6.0
Palustriella commutata	5.3
Palustriella falcata	5.0
Sesleria caerulea	4.6
Saxifraga aizoides	4.0
Pellia endiviifolia	2.5
Juncus articulatus	2.4
Agrostis stolonifera	2.4
Eriophorum angustifolium	2.0
Carex panicea	1.8
Ctenidium molluscum	1.7
Carex lepidocarpa	1.7
Calliergonella cuspidata	1.5
Hymenostylium insigne	1.5
Orthothecium rufescens	1.1
Seligeria oelandica	1.0
Aneura pinguis	0.9
Angelica sylvestris	0.8

3.3 Relationships between Groups

3.3.1 Non-metric Multidimensional Scaling (NMS)

3.3.1a General Results

NMS recommended a 3-dimensional solution. The final stress was 16.34 which is indicative of a valid solution for the number of samples (McCune and Grace 2002). A Monte Carlo test showed that the probability of a similar stress value being obtained by chance was low (p=0.0040). The final instability was very low (<0.00001), indicating that the ordination was a stable solution. Axis 2 represents the most variance (r^2 = 0.303) and the total variance represented by this 3-dimensional solution is 78.7% (Table 3.11).

Table 3.11: Variance represented by each axis

Axis	Variance (r^2) for each Axis	Cumulative r^2
1	0.216	0.216
2	0.303	0.519
3	0.268	0.787

3.3.1b Plant communities and environmental variables in NMS

The NMS ordination of samples (Figs 3.10, 3.11 and 3.12) shows that, while the communities overlap, they can nevertheless be distinguished as occupying separate parts of 3-dimensional ordination space. Group 4 lies in the central part of the ordination between Groups 1, 2 and 3 on the one hand, and Groups 5, 6 and 7 on the other. The position of Group 8 is more complex; in Fig. 3.10 and Fig. 3.11, it lies closest to Groups 5, 6 and 7, but in Fig 3.12 it is closer to Groups 1, 2 and 3 (discussed further below in relation to environmental variables).

An overlay of the most strongly correlated species (r^2>0.2) shows that *Geranium robertianum, Palustriella commutata, Eucladium verticillatum* and *Brachythecium rivulare* are, for the most part, associated with Groups 1, 2 and 3, while *Mentha aquatica, Molinia caerulea, Schoenus nigricans, Carex panicea, C. lepidocarpa, Palustriella falcata, Campylium stellatum, Ctenidium molluscum* and *Calliergonella cuspidata* are more prevalent amongst Groups 5, 6 and 7. Patterns of shared species are further discussed below (Section 3.3.2) using multi-level pattern analysis.

In tandem with similarities in species composition, Groups 1 to 3 also share in common certain abiotic variables which distinguish them from Groups 5 to 7 and they differ in numbers of species

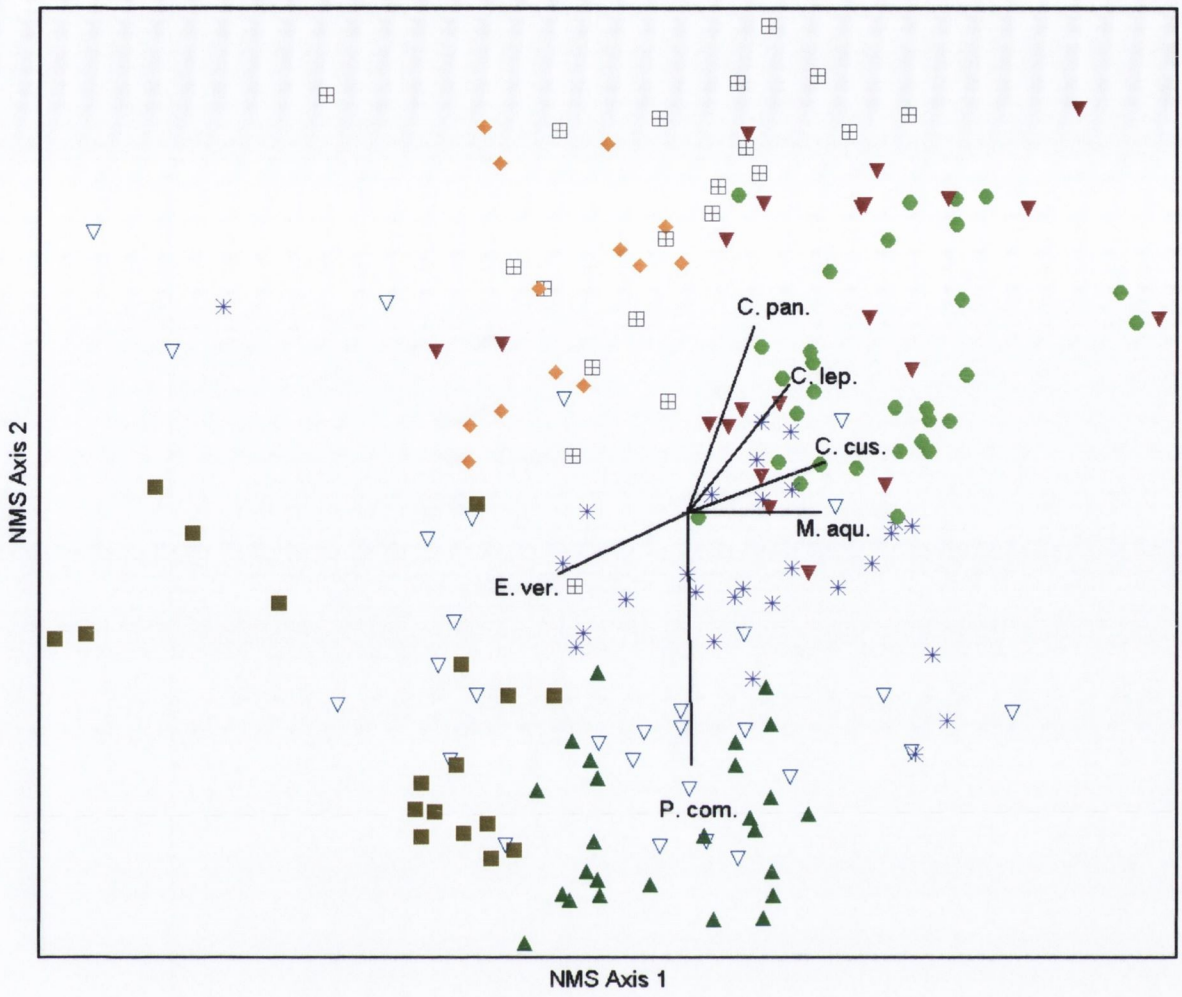
per unit area. Those variables most strongly correlated with the ordination axes (r^2 >0.20), using Pearson correlation coefficients built in to PC-ORD, are shown in Figs 3.13, 3.14 and 3.15. The more appropriate Spearman rank correlation coefficients (and the levels at which they are statistically significant) are shown in Table 3.12. Fig. 3.16 shows the relationship of environmental variables to the ordination axes based on Spearman rank correlation coefficients which are very highly statistically significant (*** p<0.001).

Slope and cascade tufa are significantly opposed to paludal tufa on all three axes (Table 3.12); tufa cascades form only on steep slopes, while paludal tufa forms on level ground. Decreasing slope is most strongly correlated with Axis 1; cascade tufa, stream crust tufa, dripping water, bare tufa and bare stone also decrease significantly along Axis 1, while paludal tufa, pools, leaf litter and number of species increase. Thus, for example, the steeply sloping Group 1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades, characterised by massive cascades of tufa, often bare and with plentiful dripping water have low Axis 1 scores; in contrast, Group 6 *Carex lepidocarpa* Small Sedge Springs, which typically occur on level ground with paludal tufa, pools of water and a diverse range of species, and have high Axis 1 scores. Axis 2 – which represents the greatest amount of variance – is most strongly correlated with decreasing tree canopy; slope, cascade tufa and dripping water also decrease significantly, while paludal tufa, non-tufa and number of species increase. This is depicted, for example in the contrast between Group 2 *Palustriella commutata-Geranium robertianum* Springheads – typical of hillside woodlands with tufa cascades – and the unshaded, sedge-dominated communities of Groups 5 to 7 on level ground with paludal tufa which is sometimes very weakly formed. The correlation coefficients for Axis 3 are somewhat lower and several groups overlap in the central part of this axis. The strongest relationship is with increasing tree canopy, along with cascade tufa, trickling water and altitude; paludal tufa decreases along Axis 3. Two groups are diametrically opposed on this axis: Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes (with high Axis 3 scores) and *Schoenus* springs (with low Axis 3 scores). The former is characterised by water trickling over tufa cascades, usually in woodland settings, while the latter is unshaded and forms paludal tufa.

Group 8 samples are located on moderately steep slopes, much like Groups 1 to 3, and this is reflected on their position on Axis 1. They lack woodland canopy and are positioned amongst the sedge dominated Groups 5 to 7 on Axis 2; all four groups also contain relatively high numbers of species per sample. Group 8 is centrally located on Axis 3, occurring at high altitudes but without woodland canopy cover.

Table 3.12: Spearman rank correlation coefficients (r_s) for environmental variables (and number of species per sample) with NMS axes. Correlation coefficients which are both statistically significant at p<0.001 and have r_s >0.500 are shown in bold. Dunn- Šidák method applied to correct for multiple comparisons.

Variable	Axis 1		Axis 2		Axis 3	
Altitude	-0.039		-0.119		0.318	***
Slope	**-0.753**	***	-0.420	***	0.280	**
Cascade tufa (% cover)	**-0.504**	***	**-0.530**	***	0.322	***
Paludal tufa (% cover)	**0.574**	***	0.354	***	-0.358	***
Stream crust (% cover)	-0.346	***	0.209		0.050	
Non-tufa (% cover)	0.173		0.435	***	-0.100	
Trickling water (% cover)	-0.234		-0.167		0.349	***
Pools (% cover)	0.411	***	0.239	*	-0.195	
Dripping water (% cover)	**-0.536**	***	-0.329	***	-0.015	
Bare tufa (% cover)	-0.392	***	-0.094		0.048	
Leaf litter (% cover)	0.404	***	0.139		-0.176	
Bare stone (% cover)	-0.443	***	0.181		-0.067	
Tree canopy (% cover)	-0.275	**	**-0.685**	***	0.418	***
No. of species	0.457	***	**0.521**	***	-0.131	

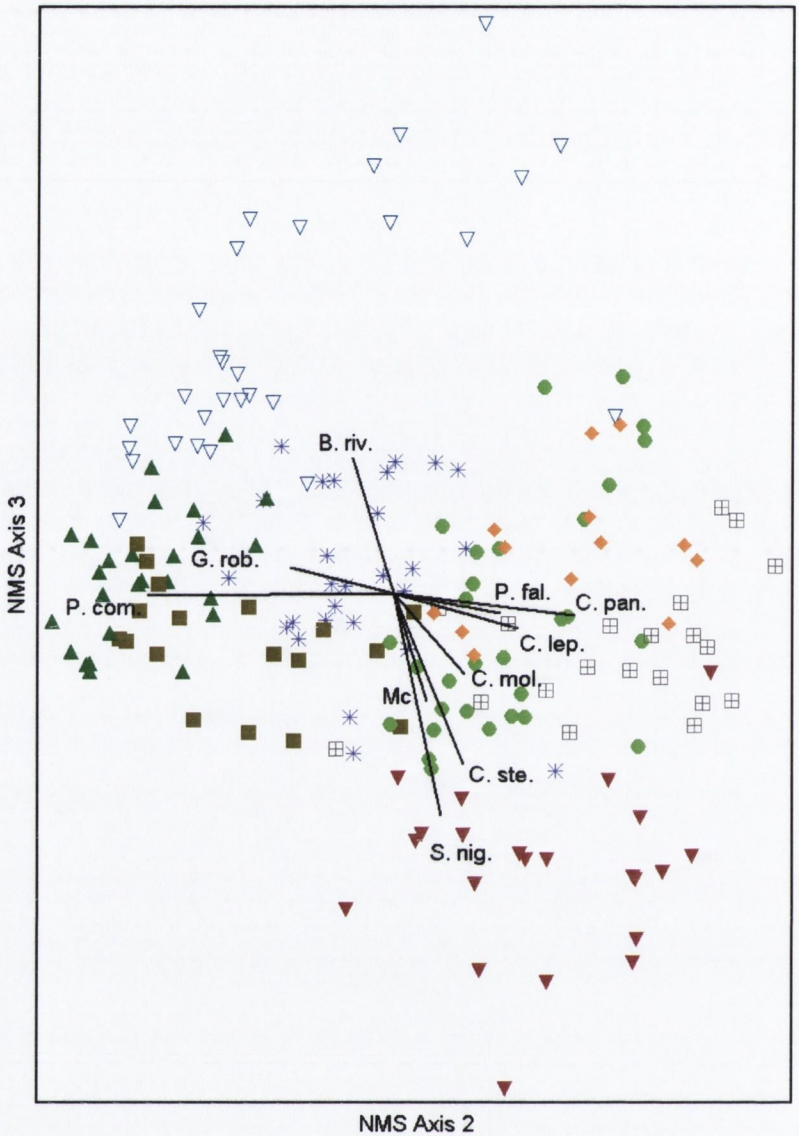


Plant Communities (Fuzzy Cluster Groups)

- Gr. 1: E. verticillatum-P. endiviifolia Tufa Cascades
- Gr. 2: P. commutata-G. robertianum Springheads
- Gr. 3: B. rivulare-P. riparioides Streams/Flushes
- Gr. 4: P. commutata-A. stolonifera Springheads
- Gr. 5: Schoenus Springs
- Gr. 6: C. lepidocarpa Small Sedge Springs
- Gr. 7: P. falcata-C. panicea Springs
- Gr. 8: S. aizoides-S. oelandica Springs

Fig. 3.10: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities and strongly correlated plant species (Pearson product-moment correlation $r^2>0.2$).
Variance (r^2) values of axes: Axis 1 = 0.216 Axis 2 = 0.303.

C. cus. = *Calliergonella cuspidata*, C. lep. = *Carex lepidocarpa*, C. pan. = *Carex panicea*
E. ver. = *Eucladium verticillatum*, M. aqu. = *Mentha aquatica*, P. com = *Palustriella commutata*.



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- Gr. 8: S. aizoides-S. oelandica Springs

Fig. 3.11: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities and strongly correlated plant species (Pearson product-moment correlation $r^2>0.2$).

Variance (r^2) values of axes: Axis 2 = 0.303 Axis 3 = 0.268

B. riv. = *Brachythecium rivulare*, C. lep. = *Carex lepidocarpa*, C. mol = *Ctenidium molluscum*
C. pan. = *Carex panicea*, C. ste. = *Campylium stellatum*, G. rob. = *Geranium robertianum*
M.c. = *Molinia caerulea*, P. com = *Palustriella commutata*, P. fal = *P. falcata*, S. nig. = *Schoenus nigricans*.

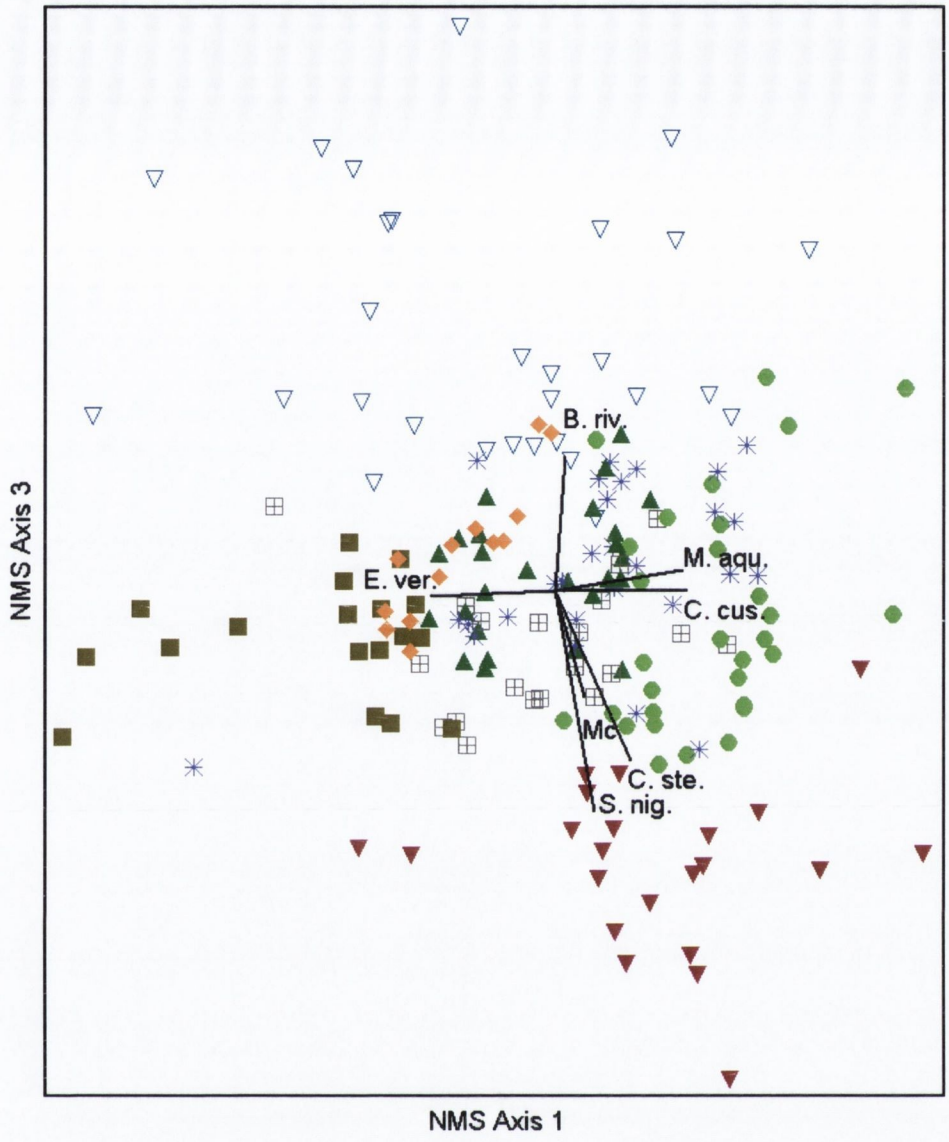

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Fig. 3.12: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities and strongly correlated plant species (Pearson product-moment correlation $r^2>0.2$).
Variance (r^2) values of axes: Axis 1 = 0.216 Axis 3 = 0.268

B. riv. = *Brachythecium rivulare*, C. cus. = *Calliergonella cuspidata*, C. ste. = *Campylium stellatum*, E. ver. = *Eucladium verticillatum*, M. aqu. = *Mentha aquatica*, M.c. = *Molinia caerulea* S. nig. = *Schoenus nigricans*.

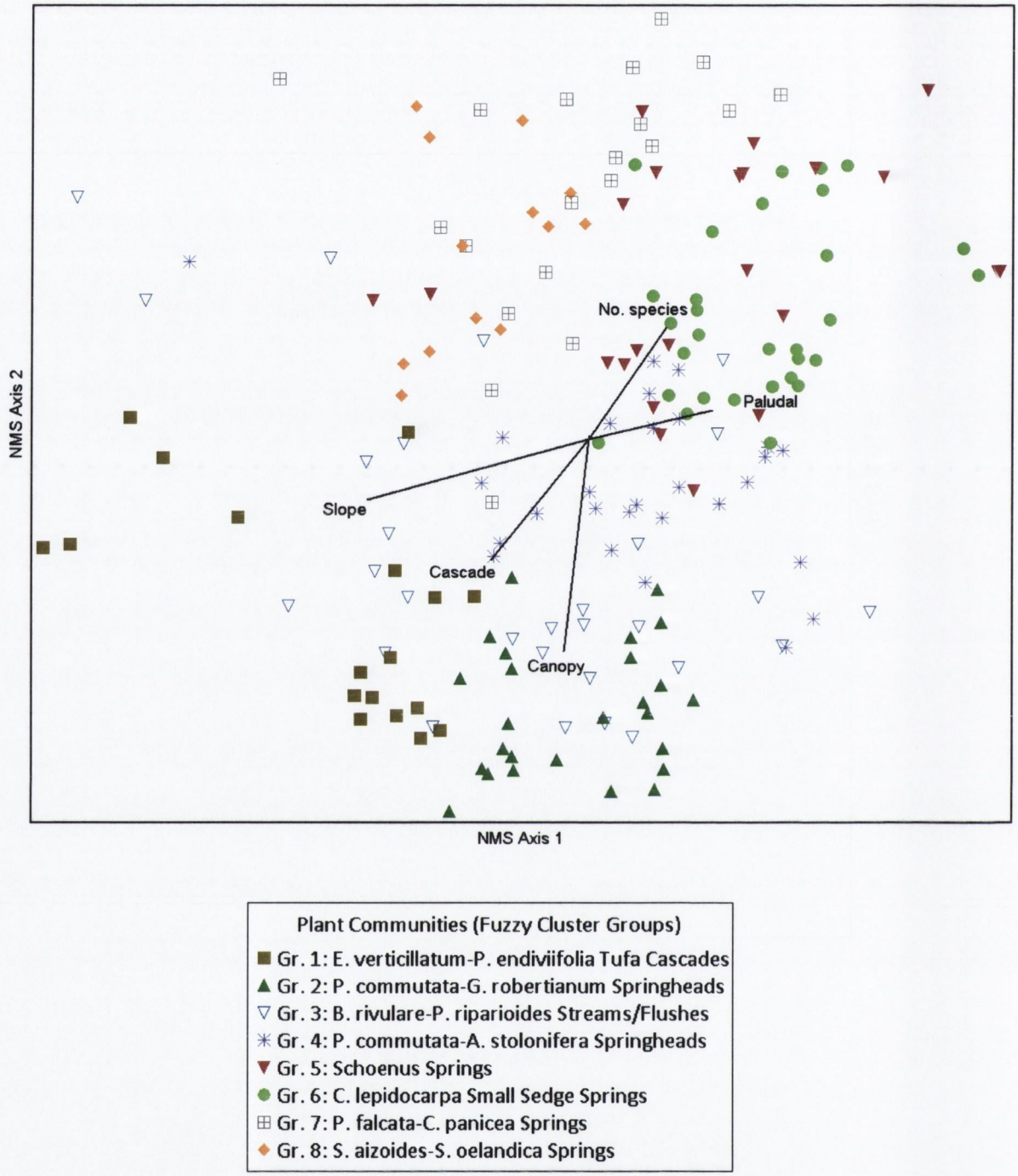
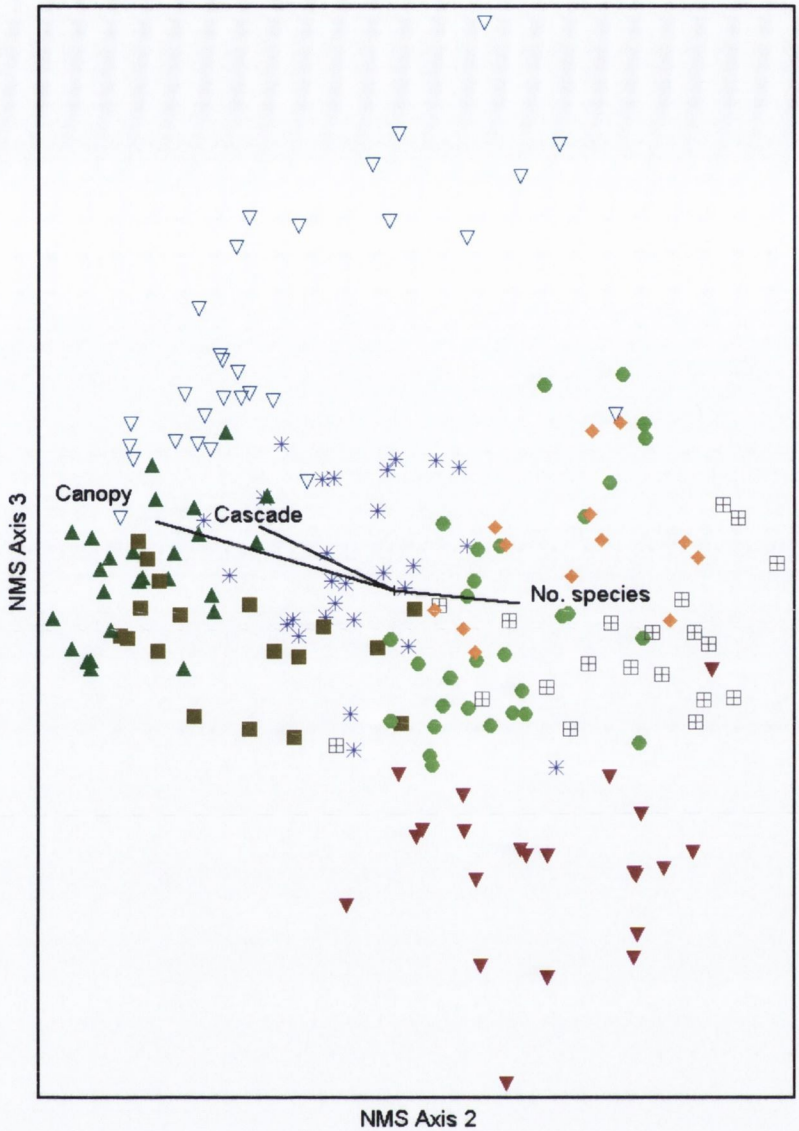


Fig. 3.13: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities and strongly correlated environmental variables (Pearson product-moment correlation $r^2>0.2$; see Fig. 3.16 for Spearman rank correlations).

Variance (r^2) values of axes: Axis 1 = 0.216 Axis 2 = 0.303.



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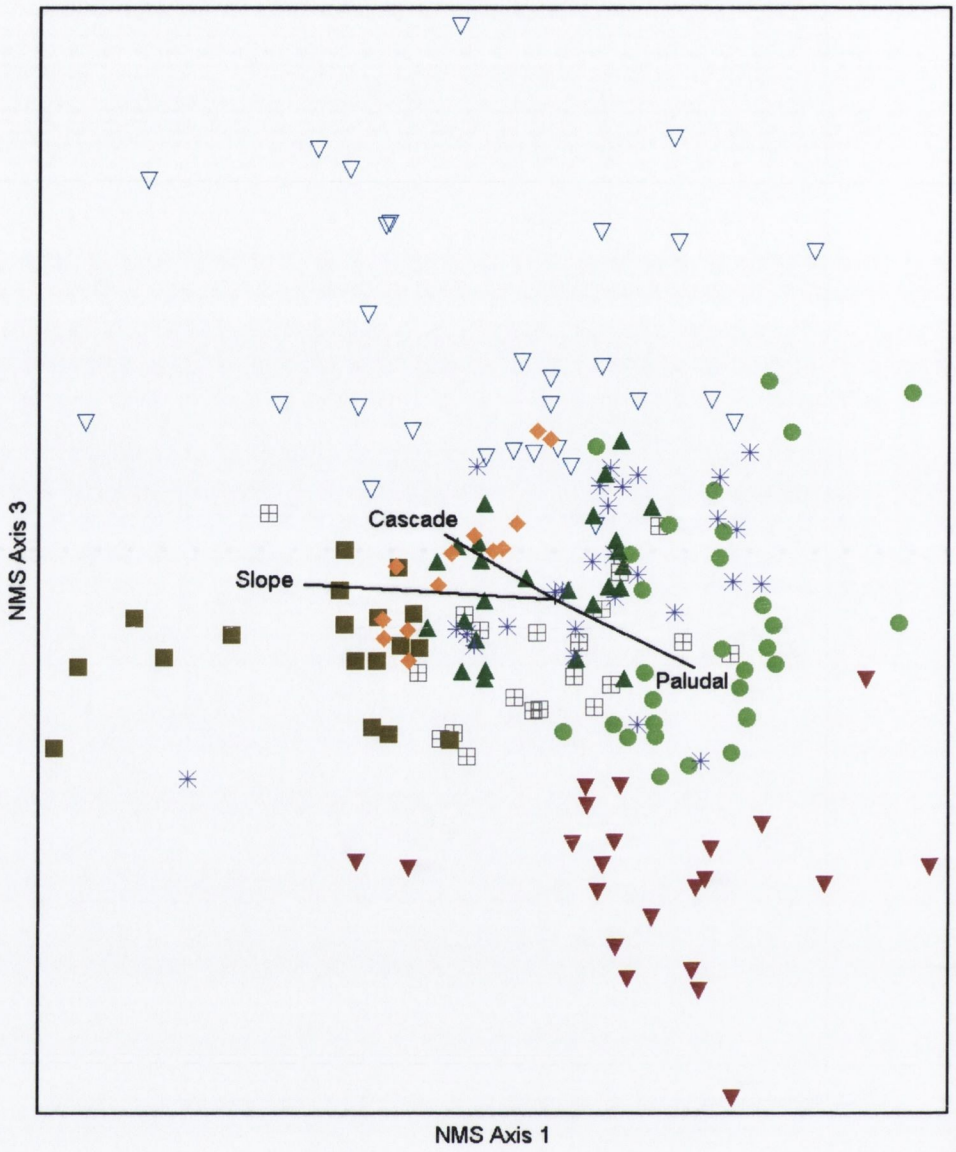
- Gr. 8: S. aizoides-S. oelandica Springs

Fig. 3.14: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities and strongly correlated environmental variables (Pearson product-moment correlation $r^2>0.2$; see Fig. 3.16 for Spearman rank correlations).

Variance (r^2) values of axes: Axis 2 = 0.303 Axis 3 = 0.268



Plant Communities (Fuzzy Cluster Groups)

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- Gr. 6: C. lepidocarpa Small Sedge Springs
- Gr. 7: P. falcata-C. panicea Springs
- Gr. 8: S. aizoides-S. oelandica Springs

Fig. 3.15: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities and strongly correlated environmental variables (Pearson product-moment correlation $r^2>0.2$; see Fig. 3.16 for Spearman rank correlations).

Variance (r^2) values of axes: Axis 1 = 0.216 Axis 3 = 0.268

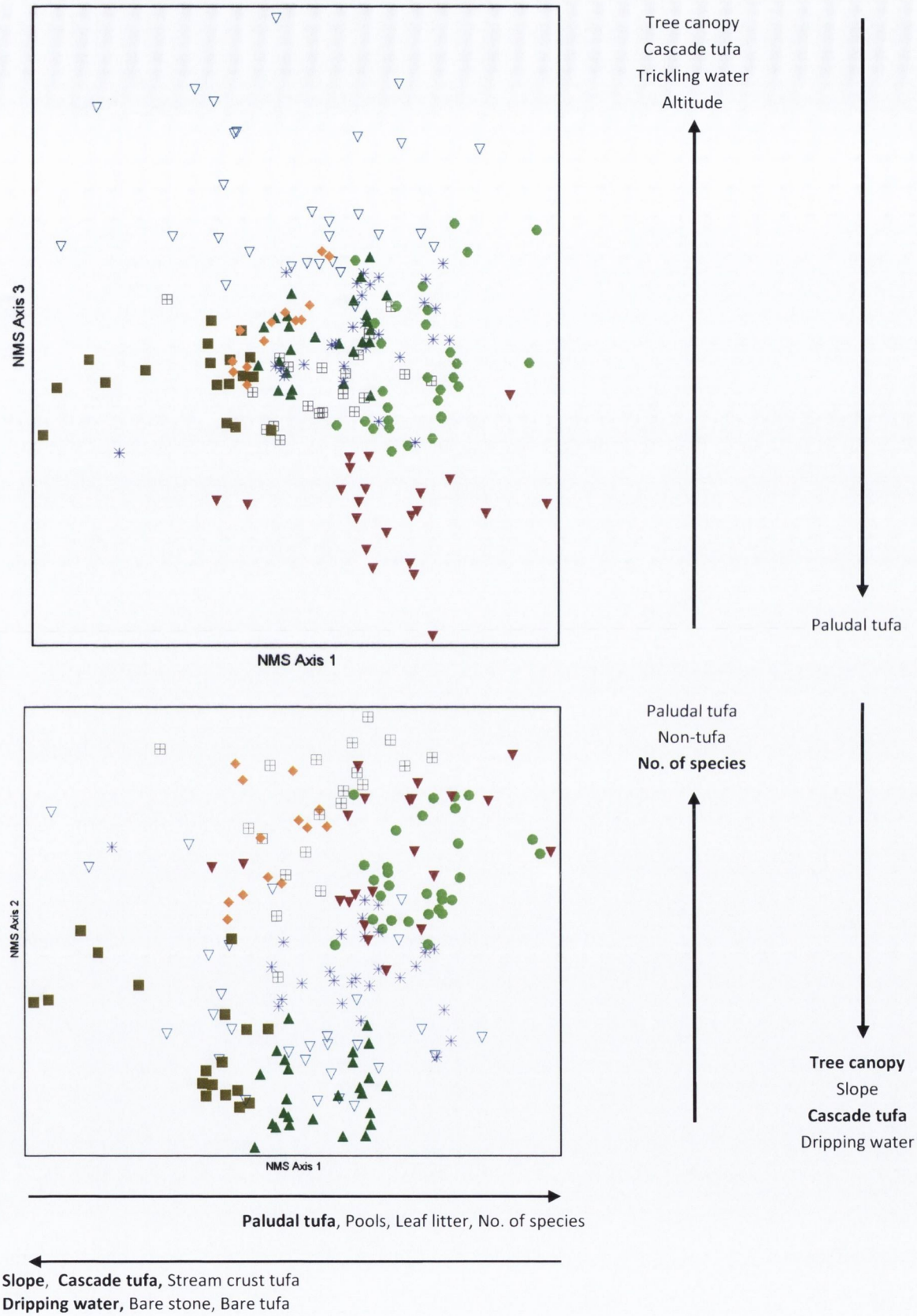


Fig. 3.16: Relationship between NMS ordination and environmental variables, calculated by Spearman rank correlation coefficients, $p<0.001$. Variables in bold type have $r_s > 0.5$ (see Table 3.12 above). Plant community symbols as in Fig 3.15 above.

3.3.2 Multi-level Pattern Analysis

Multi-level pattern analysis shows with which group, or set of groups, each species is most strongly associated. ISA yielded 108 species statistically significant to single groups; analysis by multi-level pattern analysis, yielded 123 species statistically significant to a group or a set of groups, 67% of the total number tested by this method. Selected species which are highly significant indicators are shown in Table 3.13; for full results, see App. III. Forty five species (37% of statistically significant species) are indicators of a single group. Most of these (60%) are indicators of Group 8. (The list matches the very highly significant indicator species identified by ISA, except that *Festuca rubra* and *Aneura pinguis*, instead of being allocated solely to Group 8, are here spread across several groups.) Other very highly significant indicators of single groups are *Eucladium verticillatum* (Group 1), *Rubus fruticosus* (Group 2), *Platyhypnidium riparioides* (Group 3), *Schoenus nigricans* and *Scorpidium scorpioides* (Group 5), *Pedicularis palustris* (Group 6) and *Pinguicula grandiflora* (Group 7). There are no highly significant indicator species unique to Group 4.

The contrast between Groups 1 to 3 and Groups 5 to 7 is evident in multi-level pattern analysis; in keeping with its position in the centre of the ordination, Group 4 shares some indicators with both of these sets. Group 8 stands apart in having many more unique, very highly significant indicator species than any other Group, but it also shares numerous indicator species with other groups, especially Groups 5 to 7.

49% of species are indicators of subsets within Groups 5 to 8 (and sometimes Group 4, but not Groups 1 to 3). These include *Pinguicula vulgaris, Parnassia palustris, Anagallis tenella, Carex lepidocarpa, C. panicea, C. dioica, Eleocharis quinqueflora, Eriophorum angustifolium, Selaginella selaginoides, Aneura pinguis* and *Chara vulgaris*, each of which is a very highly significant indicator of a set of Groups combining at least three of Groups 5, 6, 7 and 8. Group 4 shares in common with Groups 5, 6, 7 and 8 the indicator species *Philonotis calcarea* and *Equisetum palustre*.

Conversely, 10% of statistically significant species are indicators of subsets within Groups 1 to 3 (and sometimes Group 4, but not Groups 5 to 8). These are mostly woodland species, such as *Hedera helix, Geranium robertianum, Chrysosplenium oppositifolium, Carex remota, Brachypodium sylvaticum* and *Equisetum telmateia*. However, while Groups 2 and 3 share several indicator species in common, Group 1 shares few with any other group. (Group 1 has the fewest species overall, with only 9 species per relevé on average.) Those that it does share are shared broadly across many groups (*i.e. Tussilago farfara, Festuca rubra, Agrostis stolonifera* and *Pellia endiviifolia* Table 3.13).

Table 3.13: Summary of multi-level pattern analysis for selected indicator species. For full data set, see Appendix III. *** p-value <0.001; ** p-value <0.01;

	Species	G1	G2	G3	G4	G5	G6	G7	G8	p-value
SINGLE GROUP	Eucladium verticillatum	■								***
	Didymodon tophaceus	■								**
	Rubus fruticosus		■							***
	Platyhypnidium riparioides			■						***
	Schoenus nigricans					■				***
	Scorpidium scorpioides					■				***
	Pedicularis palustris						■			***
	Pinguicula grandiflora							■		***
	Saxifraga aizoides								■	***
	Seligeria oelandica								■	***
	Hymenostylium insigne								■	***
	Orthothecium rufescens								■	***
Gr.1-3 (NOT 5-8)	Hedera helix	■	■	■						***
	Geranium robertianum		■	■						***
	Chrysosplenium oppositifolium		■	■						**
	Carex remota		■	■						***
	Brachypodium sylvaticum		■	■						**
	Brachythecium rivulare		■	■	■					***
	Equisetum telmateia		■	■	■					***
GROUPS 5-8 (NOT 1-3)	Bryum pseudotriquetrum				■		■	■	■	***
	Philonotis calcarea				■	■	■	■	■	***
	Equisetum palustre				■	■	■	■	■	***
	Molinia caerulea					■	■			***
	Campylium stellatum					■	■			***
	Scorpidium cossonii					■	■			***
	Anagallis tenella					■	■	■		***
	Eleocharis quinqueflora					■	■	■		***
	Chara vulgaris					■	■	■		**
	Selaginella selaginoides					■		■	■	***
	Pinguicula vulgaris					■	■	■	■	***
	Carex lepidocarpa					■	■	■	■	***
	Carex panicea					■	■	■	■	***
	Eriophorum angustifolium					■	■	■	■	***
	Aneura pinguis					■	■	■	■	***
	Parnassia palustris						■	■	■	***
	Carex dioica						■	■	■	**
	Palustriella falcata							■	■	***
BROAD RANGE	Cardamine pratensis		■	■	■		■			***
	Mentha aquatica			■	■		■	■		***
	Ranunculus repens		■	■					■	***
	Tussilago farfara	■			■			■	■	**
	Juncus inflexus		■		■		■			***
	Cratoneuron filicinum			■	■		■	■		***
	Pellia endiviifolia	■	■	■					■	***
	Festuca rubra	■			■	■	■	■	■	***
	Agrostis stolonifera	■	■	■	■		■	■	■	***

Only 14% of statistically significant species are indicators of subsets combining groups from both Groups 1 to 3 and Groups 5 to 8, and they are mostly species of relatively broad ecological range – for example *Cardamine pratensis, Mentha aquatica, Ranunculus repens, Juncus inflexus* and *Cratoneuron filicinum*. An exception here is *Pellia endiviifolia*, a very highly significant indicator of Groups 1, 2, 3 and 8. This species is typical of the steep slopes characteristic of these four groups; it is seldom found on level surfaces.

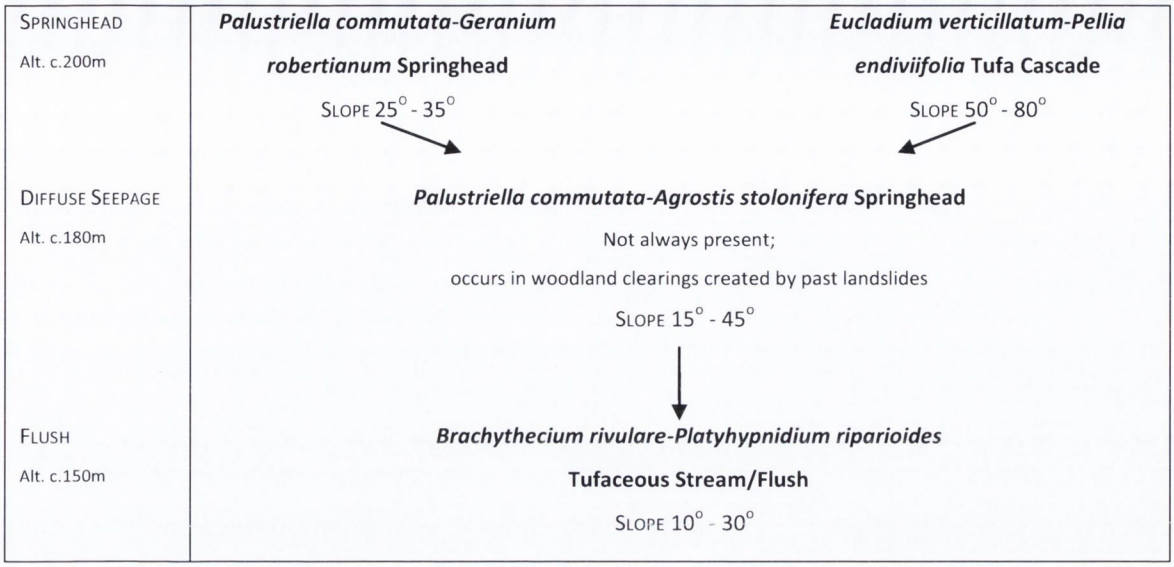
The most broadly distributed, very highly significant indicator species are *Agrostis stolonifera* (indicator of seven Groups, excluding only Group 5) and *Festuca rubra* (indicator of six Groups, excluding only Groups 2 and 3). Only one species, *Palustriella commutata*, was not found to be an indicator of any Group or set of Groups by multi-level pattern analysis, but rather was spread across all eight groups.

3.3.3 Community Combinations

Two or more of the communities described sometimes occur in combination along ecological gradients within a spring complex, most often related to steepness of slope and distance from the point at which spring water emerges.

The most evident sequences were found on wooded hillsides. These consist of either *Palustriella commutata-Geranium robertianum* Springheads (on moderate slopes) or *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades (on steep slopes) giving way below to *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes. Often the springhead vegetation occupies only a few square metres while the flush below extends over tens or even hundreds of square metres. This pattern occurs, for example, at Glenasmole, Co. Dublin. In some of the larger springs at Glenasmole prolific seepage zones occur below the springhead; very often these lack woodland canopy, having been subject to landslides in the past. At the top, the springhead is heavily petrified (either a *Palustriella commutata-Geranium robertianum* Springhead or *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascade) and below this a more extensive area of *Palustriella commutata-Agrostis stolonifera* Springhead vegetation extends as additional water seeps diffusely from the hillside. Below, the water is channelled into *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes and thence flows into Bohernabreena Reservoir (Fig. 3.17).

Fig. 3.17: Schematic relationship between spring communities on a wooded hillside at Glenasmole, Co. Dublin.



At coastal sites, this pattern is prevented from forming; spring water emerges over a spray-zone cliff or bank and the sequence is truncated by the action of the tide. At such locations, a series of parallel springs is often evident; these may belong to a single community, as at Spanish Point, Co. Clare, where *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades extend some distance along the steep cliff face. Alternatively, different communities may be represented in nearby springs. For example, near Skerries, Co. Dublin, three different communities were recorded: on a steep, heavily petrified part of the coast, *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades formed (QL154); nearby, where the ground was more gently sloping, a *Palustriella commutata-Agrostis stolonifera* Spring wound its way down the bank (QL153), while further along the beach, tufaceous deposits in a highly modified state below a drainage pipe fell into the *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Stream community (QL155). The water sources of these three samples lay in close proximity to each other, yet the communities at the point of emergence were very different.

Palustriella commutata-Agrostis stolonifera Springheads, in open or lightly shaded sites, can be associated with various communities. They frequently extend over larger areas with more diffuse seepage than their more steeply inclined woodland counterparts, *Palustriella commutata-Geranium robertianum* Springheads. On gently sloping ground, *Palustriella commutata- Agrostis stolonifera* Springheads are most often associated with *Carex lepidocarpa* Small Sedge Springs. For example, at Pollardstown Fen, the former community was recorded at a discrete area (c. 5m^2) of upwelling ground water (QL206) and the latter community was recorded where spring water dissipated (QL032, QL033). Similarly at Ballyman Glen, Co. Wicklow, the *Palustriella commutata-*

Agrostis stolonifera Springhead community was localised where seepage was most intense (QL080) and was accompanied by more diffuse *Carex lepidocarpa* Small Sedge Springs with less seepage (QL119, QL120). *Carex lepidocarpa* Small Sedge Springs can occur without any separate, discrete springhead community, as at Louisa Bridge, Co. Kildare and at Faughalstown, Co. Westmeath, where there are diffuse seepage areas with paludal tufa on gently sloping ground.

More rarely, *Palustriella commutata- Agrostis stolonifera* Springheads co-occur with *Schoenus* springs. At Cormac Reagh's Hole, Benbulbin Range, Co. Sligo, a distinct *Palustriella commutata-Agrostis stolonifera* Springhead (QL130) gives way to a flush (QL132), flanked by seepage zones (QL131); samples from both flush and seepage zones belong to the *Schoenus* Spring community. For the most part, however, *Schoenus* Springs (like *Carex lepidocarpa* Small Sedge Springs) form in areas with diffuse seepage where it is difficult to pinpoint emergence points for water. They sometimes irrigate large fen areas on almost level ground, for example at Eskeragh and Ballycurrin in Co. Mayo.

Saxifraga aizoides-Seligeria oelandica Springs seldom adjoin the other spring communities described here. Very often, spring water percolates back into the soil at the base of the cliff, leaving the springhead as an isolated wet area in the midst of otherwise dry ground. The water may then re-emerge some distance away on more gently sloping ground at the foot of the hill, usually as *Palustriella falcata-Carex panicea* Springs. There are several instances where this is the case at Glenade and nearby on Arroo Mt, both in Co. Leitrim.

Palustriella falcata-Carex panicea Springs, likewise, are seldom accompanied by other spring types. In the Burren, where they are most frequent, the spring water most often sinks again through the karst limestone a short distance below the point at which it emerges (*e.g.* at Newtown, Glennamanagh and Acres Village). Sometimes, however, this community occurs in conjunction with *Schoenus* Springs. At Rinnamona, in the Burren, *Palustriella falcata-Carex panicea* Springs flow out over limestone pavement which is flanked by diffuse *Schoenus* Springs. Ballynafagh, Co. Kildare and Dooaghtry, Co. Mayo, also contain a combination of *Palustriella falcata-Carex panicea* Springs with adjoining *Schoenus* Springs.

Brachythecium rivulare-Platyhypnidium riparioides Tufaceous Streams and Flushes sometimes form in the absence of the other communities described here. For example, at Fonthill and Woodlands in the Liffey valley in Co. Dublin, there are four instances of this community in a notably depauperate state where it occurs on watercourses modified by anthropogenic activities.

3.3.4 Weakly tufaceous samples

In ten relevés, only a trace of tufa was found, sparsely deposited on the stems of plants or on the ground surface. Two further relevés lacked any sign of tufa, although the vegetation contained typical *Cratoneurion* species (Table 3.14). These samples are distributed across Groups 4 to 8. Several of them have high membership coefficients of groups – 8 samples (67%) have membership coefficients >80% – indicating that their floristic composition is very similar to the other (more strongly tufa-forming) members of their respective groups.

Table 3.14: Relevés lacking tufa or forming only very sparse deposits. MC = Membership Coefficient.

Ref.	Relevé Name	Paludal %	Strength	Stream crust %	Non-tufa %	Group	MC%
QL014	Inis Meáin	1	2	0	99	4	89
QL160	Carlingford Marina	1	1	0	99	4	86
QL016	Ballycurrin Fen 1	1	1	0	99	5	100
QL017	Ballycurrin Fen 2	1	1	0	99	5	100
QL089	Rinnamona L. Fen 2	5	1	0	95	5	93
QL020	Knocknatulla	1	1	0	99	6	73
QL124	Ballybannon ASSI	0	-	0	100	6	93
QL138	Old Head	1	1	0	99	6	35
QL165	Kilrock Quarry 1	0	-	1	99	6	43
QL137	Knocknagur	0	-	0	100	7	90
QL166	Kilrock Quarry 2	0	-	5	95	8	48
QL211	Murlough Bay C	1	1	0	99	8	82

3.4 Discussion

The eight Irish 'petrifying spring' communities described are distinct from each other in species composition and in abiotic characteristics. While the community groupings and the NMS ordination are derived from species data, MRPP shows that the groupings are also statistically significant for abiotic variables. There is some degree of overlap between these communities and not all samples are a good fit within this arrangement but, on the whole, each community is defined by a core group of samples which is very different from the core samples of the other communities.

The *Saxifraga aizoides-Seligeria oelandica* Spring community is of particular ecological interest. The preponderance of species which are rare, some in a European or even worldwide context, makes this a community of exceptionally high conservation value. It is strongly defined by numerous indicator species which, even by multi-level pattern analysis, are very highly significant indicators of this single Group. In Ireland, its fullest expression is confined to the biogeographical range of *Seligeria oelandica* in permanently irrigated springs, usually on north-facing cliffs of the limestone uplands of Counties Sligo, Leitrim and Fermanagh. Here, it is a highly characteristic and distinctive feature of the landscape, often discernible from a distance where thin films of spring water spill over almost bare cliff faces, sometimes causing a conspicuous whitish discolouration on the darker rock surface. The community extends in a somewhat depauperate form onto the coastal cliffs of north-east Antrim, the only other locality for *Saxifraga aizoides* in Ireland; however, the rare bryophyte species of the community are absent there.

This community, though striking in its level of species richness, is not strongly tufa forming. Very often, there is little more than a thin layer of soft, unconsolidated tufa over part of the ground surface. Conversely, spring communities which are spectacular in their ability to form tufa typically contain few species, since the extreme chemical environment is hostile to most. Such springs are best exemplified in *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades. This community thrives on damp, vertical tufa faces where the rapid depositional process often provides a striking record of plant structure and hydrological features in the fabric of the tufa deposits. In contrast to *Saxifraga aizoides-Seligeria oelandica* Springs, the thickness and proliferation of tufa in *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades provides fewer micro-niches; steep slopes are a feature of both communities, but in the former, crevices and meagre pockets of soils create a more varied substrate for plants to root in and exposed rock surfaces accommodate the tiny *Seligeria* species.

Brachythecium rivulare-Platyhypnidium riparioides Tufaceous Streams are, likewise, often very strongly tufa forming but low in species diversity. Their species composition is less ecologically distinctive than *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades; *Cratoneuron filicinum* often replaces *Palustriella commutata* and wetland generalists such as *Nasturtium officinale* and *Ranunculus repens* are characteristic.

Much more characteristic are the two communities in which *Palustriella commutata* is both constant and most abundant. *Palustriella commutata-Agrostis stolonifera* Springheads form the central expression of the habitat, from which other communities depart along various ecological gradients. This community has a wide geographical distribution but is somewhat lacking in distinctive indicator species. It encompasses both springhead vegetation dominated by *Palustriella commutata* and the associated flushes where wetland generalists such as *Mentha aquatica*, *Filipendula ulmaria* and *Juncus articulatus* increase; the samples show a continuous gradation from one to the other. The low mean silhouette width and low membership coefficients suggest that this group is poorly defined; further sampling might show that division into separate spring and flush communities is warranted. The woodland counterpart, the *Palustriella commutata-Geranium robertianum* Springhead community, is a more tightly defined community; associated flushes usually constitute separate *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Stream and Flush communities.

Slope plays an important role in determining which communities will form. Steep slopes allow water to drain away quickly, whereas gentle slopes cause it to become impounded more easily; fast flowing water is better aerated due to turbulence than static water in pools. The *Saxifraga aizoides-Seligeria oelandica* Spring communities show a preference for thin films of constantly moving water, compared, for example, to the *Schoenus* Spring and *Carex lepidocarpa* Small Sedge Spring communities which form in much more slowly moving water and the *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes where the depth of water is somewhat greater.

Cascade tufa forms only on relatively steep slopes while paludal tufa is characteristic of gently sloping and level ground. Woodland springs in the present study are associated with steep slopes and often massive tufa cascades. Anthropogenic factors contribute to this; woodlands most often survive on steeper slopes whereas they have been cleared from level sites for agricultural usage.

MRPP found no statistically significant difference between Groups 5 and 6 based on the abiotic variables tested: both are on level, unshaded ground, both form paludal tufa – cascade tufa is entirely absent from both – and both contain plentiful pools but have very little flowing water. In spite of these abiotic similarities, these groups are distinct in their species composition; for

example, there are no shared species in constancy classes V or IV. Similarly, Groups 4 and 7 do not differ significantly in their abiotic characteristics according to MRPP analysis: both form on unshaded, moderate slopes, tufa can consist of cascade or paludal deposits and water occurs as both trickling streams and small pools. Nevertheless, species composition of the two communities is distinct.

Group 1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades



Photo 3.1: Group 1 tufa cascade near Skerries Co. Dublin (QL154) with *Eucladium verticillatum, Palustriella commutata*, *Didymodon tophaceus* and *Festuca rubra*. The red alga *Chroothece* sp. was collected from the right hand side of the tufa cascade (approx. location indicated by arrow; see also Photo 3.2). Tufa at the base of the cascade has cemented beach pebbles into a solid mass ('cemented rudites' Table 1.1, Pentecost 1995). March 2012.



Photo 3.2: *Chroothece* sp. forms an orange mucilaginous patch (indicated by arrow) on damp tufa beside QL154 near Skerries, Co. Dublin, October 2012.

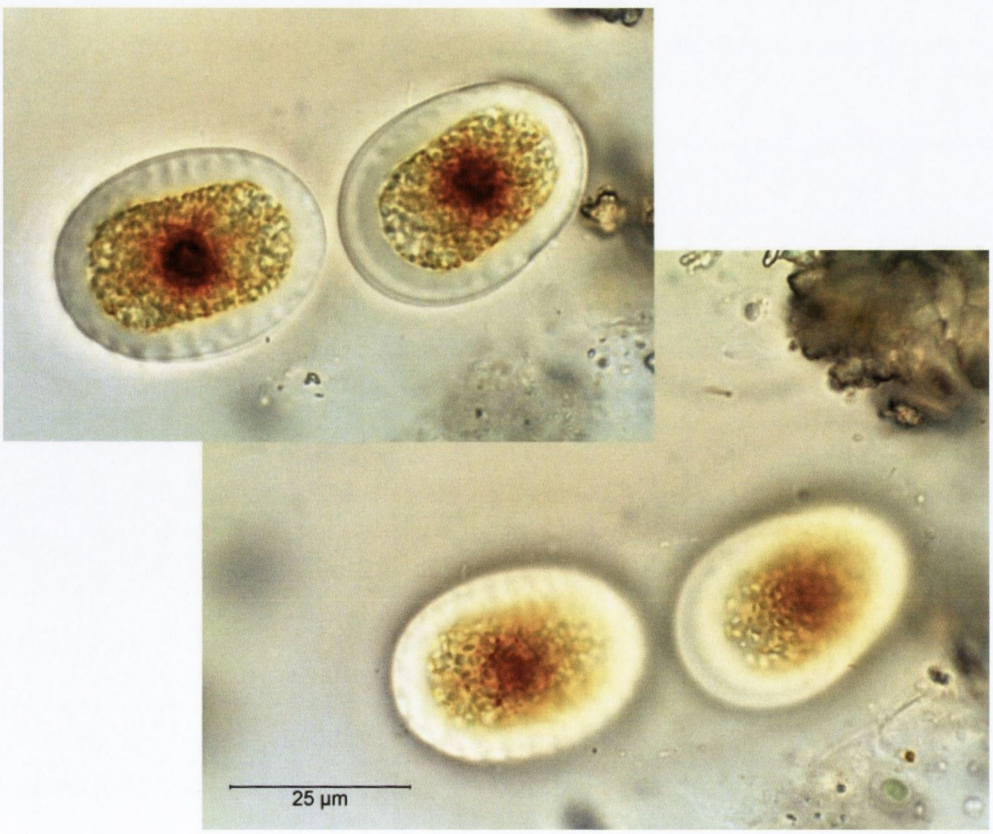


Photo 3.3: Cells of *Chroothece* sp. (collected at Spanish Point, below). Photograph and identification kindly provided by Dr Chris Carter, April 2012.



Photo 3.4: QL051 Spanish Point, Co. Clare, April 2012. Coastal tufa cascade with *Eucladium verticillatum*, *Pellia endiviifolia* and smaller amounts of *Didymodon tophaceus* and *Palustriella falcata*. *Plantago maritima* is the most abundant vascular plant along with *Samolus valerandi*, *Agrostis stolonifera* and *Festuca rubra*. The red alga, *Chroothece* sp., also occurs within this sample (approx. location indicated by arrow).



Photo 3.5: Inland tufa cascade with *Palustriella commutata, Eucladium verticillatum, Pellia endiviifolia, Didymodon tophaceus* and *Bryum pseudotriquetrum*. Vascular plants include *Eupatorium cannabinum* and *Tussilago farfara*. QL013 Glenasmole, Co. Dublin, March 2013.



Photo 3.6: Tufa formed in association with *Pellia endiviifolia* at QL013 (Photo 3.5) Glenasmole, May 2011.



Photo 3.7: Tufa in the form of stalactites, interspersed with patches of *Eucladium verticillatum* on coastal tufa cascade near Skerries, May 2013.

Group 2 *Palustriella commutata-Geranium robertianum* Springheads



Photo 3.8: QL193 Moneyduff Woods with *Palustriella commutata* (90% cover), *Asplenium scolopendrium, Geranium robertianum* and *Carex remota*. Strongly formed paludal tufa underlies the vegetation and the rivulet is lined with oncoids/ooids. July 2013



Photo 3.9: Rock face at Glencar, Co. Leitrim (QL195) with *Adiantum capillus-veneris* amongst *Palustriella commutata* and *Sesleria caerulea* in a damp, tufaceous rock crevice. (Arrow indicates location of *A. capillus-veneris*). July 2013.



Photo 3.10: '*Cratoneuron* drip-zone' communities (Ferreira 1978) at Knocknarea Glen, Co. Sligo. Mounds of *Palustriella commutata* are irrigated from above by dripping water. June 2010.



Photo 3.11: Stream bank tufa cascade dominated by *Palustriella commutata* with small amounts of *Carex remota, Didymodon tophaceus, Eucladium verticillatum* and *Pellia endiviifolia*. QL059 Glinsk Grove, Slieve Bloom Mountains, May 2012.



Photo 3.12: QL060 (opposite side of stream to QL059, Photo 3.11 above) with patchy *Palustriella commutata* and *Equisetum telmateia*. May 2012.

Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes



Photo 3.13: Flush in Knockree, Co. Wicklow (QL053, April 2012). *Palustriella commutata* and *Agrostis stolonifera* are the predominant species, along with *Ranunculus repens*, *Carex remota, Brachypodium sylvaticum* and *Brachythecium rivulare*. The flushed ground surface consists of oncoids/ooids and stream crust tufa along with plant debris which becomes incorporated into the accumulating tufa.



Photo 3.14: *Platyhypnidium riparioides* and *Brachythecium rivulare* on a large tufa cascade (>50m^2) at Woodlands, Co. Dublin, below the overflow from a golf course lake. (QL159, May 2013)



Photo 3.15: Stream with cascade and stream crust tufa at Glenasmole, Co. Dublin (QL188, TB07, June 2013). *Equisetum telmateia* is dominant, accompanied by *Mentha aquatica, Ranunculus repens* and *Rubus fruticosus*. Bryophytes form small colonies on damp tufa above the main flow of water.



Photo 3.16: Small (partly eroded) tufa dams with *Palustriella commutata* and green, filamentous algae on a stream flowing into the River Liffey, near Palmerstown, Co. Dublin. (QL157, May 2013)



Photo 3.17: Massive tufa cascade in agricultural setting at Hartwell, Co. Kildare, with *Petasites hybridus, Holcus lanatus, Ranunculus repens, Chrysosplenium oppositifolium, Nasturtium officinale* and *Apium nodiflorum*. (QL175, June 2013)



Photo 3.18: Spring head at Cormac Reagh's Hole, Co. Sligo, with *Palustriella commutata, Festuca rubra, Agrostis stolonifera, Carex flacca* and *C. panicea* (QL130, September 2012). Weak paludal tufa forms beneath the vegetation. (See also Photos 3.24 and 3.25 below.)



Photo 3.19: Seepage and flush at QL063 Glenasmole, Co. Dublin with cascade tufa and oncoids/ooids, May 2012. *Palustriella commutata* is abundant, along with *Eupatorium cannabinum*. Graminoids include *Festuca rubra, Agrostis stolonifera, Deschampsia cespitosa, Carex flacca* and *Juncus articulatus*.



Photo 3.20: Spring head tufa cascade dominated by *Palustriella commutata* (brown patches) and *Festuca rubra* (QL153, May 2013). Rapidly forming tufa cements pebbles on the beach at the base of the cascade.



Photo 3.21: Group 5 *Schoenus* springs at Corhawnagh, Co. Sligo, September 2012. *Schoenus nigricans* dominates the vegetation, forming tussocks amongst an underlayer of brown mosses. Paludal tufa is heavily precipitated, forming a conspicuous white layer and small pools of water are frequent.



Photo 3.22: Keelhilla Fen, Burren, with *Schoenus nigricans* and *Eriophorum latifolium*. The uncommon leafy liverwort *Leiocolea bantriensis* occurs here. (Part of QL072, May 2012)



Photo 3.23: Heavily precipitated paludal tufa at Eskeragh, Co. Mayo (June 2012) with *Schoenus nigricans*.



Photo 3.24: Cormac Reagh's Hole, Tievebaun Mt, Co. Sligo. Tufaceous Group 5 flush with *Schoenus nigricans* below bright green spring head dominated by *Palustriella commutata* (QL130, Group 3, Photo 3.18 above). September 2012.



Photo 3.25: Cormac Reagh's Hole flush with *Schoenus nigricans, Pinguicula vulgaris* and *Juncus articulatus* (QL132 Sept. 2012). Oncoids/ooids are the predominant form of tufa. *Seligeria oelandica* occurs on damp rock surfaces.

Group 6 *Carex lepidocarpa* Small Sedge Springs



Photo 3.26: Small sedges and brown moss vegetation at Louisa Bridge, Leixlip, Co. Kildare (QL122, June 2012). Paludal tufa of intermediate strength underlies the vegetation while the pool is lined with oncoids/ooids.



Photo 3.27: Pollardstown Fen, Co. Kildare (QL204, July 2013) where *Tomentypnum nitens* (below) grows, amongst *Juncus subnodulosus, Phragmites australis* and *Schoenus nigricans*.



Photo 3.28: The rare moss, *Tomentypnum nitens*, which is 'Vulnerable' in Ireland, growing in Pollardstown Fen beneath tall rush vegetation, September 2011.



Photo 3.29: Springs close to Lough Derravaragh, Co. Westmeath (QL161-QL164) with species-rich vegetation containing *Eriophorum angustifolium* and *Schoenus nigricans* (June 2010). This field is grazed seasonally by cattle.



Photo 3.30: Detail of QL162 at Faughalstown, May 2013, with strongly-formed paludal tufa, *Philonotis calcarea, Bryum pseudotriquetrum, Equisetum palustre, Juncus articulatus, Agrostis stolonifera* and small sedge species.

Group 7 *Palustriella falcata–Carex panicea* Springs



Photo 3.31: *Pinguicula grandiflora* growing in a mat of *Palustriella falcata* with small sedges including *Carex panicea*. Moneen Mountain, Burren, Co. Clare, May 2012.



Photo 3.32: Coastal dune slack grazed by sheep, Dooaghtry, Co. Mayo (QL093, June 2012). *Catoscopium nigritum* grows along the damp margins of the dune slack with *Palustriella falcata* and bright green clumps of *Philonotis calcarea*.



Photo 3.33: The rare moss *Catoscopium nigritum* with capsules at Dooaghtry, Co. Mayo, June 2012.



Photo 3.34: Stream crust tufa on flushed limestone pavement, with pockets of *Palustriella falcata, Pinguicula grandiflora* and small sedges. Paludal tufa forms amongst the vegetation. (QL075 Moneen Mountain, May 2012)



Photo 3.35: Tufa-encrusted *Palustriella falcata* on flushed limestone pavement at Moneen Mountain, Co. Clare. May 2012.



Photo 3.36: Tufa cascade with *Palustriella falcata*, sedges and oncoids/ooids at Glenade, Co. Leitrim (QL198, July 2013).



Photo 3.37: Thomastown Quarry, Co. Kilkenny (QL168, May 2013) with paludal tufa amongst vegetation and marl lining the central part which is flooded for part of the year.

Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs



Photo 3.38: Gleniff (Annacoona) on the north side of the Benbulin Range, where species-rich vegetation, with *Saxifraga aizoides, Seligeria oelandica, S. patula, Hymenostylium recurvirostrum* var. *insigne* and *Orthothecium rufescens,* occurs on flushed cliffs. Arrows indicate the main (horizontal) spring lines. September 2012.



Photo 3.39: *Saxifraga aizoides* (centre) with black patches of *Seligeria* spp and *Jungermannia atrovirens* on flushed rocks, coated in a thin film of tufa. Gleniff, Co. Sligo, September 2012.



Photo 3.40: The rare moss species *Seligeria oelandica* with capsule (centre, *c*.3-5mm tall) on tufa (near Eagle's Rock, Benbulbin Range, July 2013).



Photo 3.41: *Saxifraga aizoides* with *Orthothecium rufescens* (red shoots, centre)in seepage at Eagle's Rock, above Glenade, Co. Leitrim. (QL196, July 2013)



Photo 3.42: *Hymenostylium recurvirostrum* var. *insigne*, on flushed rocks at Benwiskin, Co. Sligo. (QL136, September 2012)



Photo 3.43: Species-rich seepage on NNW facing cliffs of Benbulbin (QL135, September 2012). In spite of the expanse of bare rock, this sample contained 48 species, one of the highest numbers recorded.



Photo 3.44: Waterfall at Black Head, Co. Clare with stream crust tufa (QL090, June 2012). *Orthothecium rufescens* has its only station outside of the north-west in this locality.



Photo 3.45: Seepage at Murlough Bay (QL211, July 2013) with *Cratoneuron filicinum, Calliergonella cuspidata, Palustriella falcata* and *Saxifraga aizoides* and *Pinguicula vulgaris* on laterite soil.



Photo 3.46: Tufa cascade at Murlough Bay, Co. Antrim (QL208, July 2013) with *Saxifraga aizoides*, *Palustriella falcata* and *P. commutata*.

4. Syntaxonomy of Groups

In this chapter, the eight communities into which my samples fall are compared with other published petrifying spring communities as well as with some relevés recorded during the present study in Germany.

Kuhn's (1937) *Hypnum commutatum-Cratoneuron filicinum* Community (later amended to the *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977) was described from springs and streams in the Schwäbische Alb (Swabian Alps) south of Stuttgart. This *locus classicus* was visited as part of the present project in July 2012 and relevés were recorded from tufa-forming springs and streams at Urach, Güterstein, Talheim, Dießen, Glatt and Wimsen (Fig. 4.1, Photos 4.1 to 4.14). Ten relevés were recorded in total, using the same methods as for Irish relevés (see Section 3.1.1).



Fig 4.1: Location of German samples recorded in July 2012 (black circles). Insert shows location of main map within Germany.

4.1 Statistical analysis

Sørensen coefficients of similarity were calculated for my plant communities compared with published communities from Great Britain and from different parts of Europe. It is important to note, however, that the published data sets on which these calculations are based are in themselves summaries, not the original data in their raw state. All species present in my fuzzy cluster relevés were included in the calculations, but species absent from Ireland were not included unless they were constant in at least one of the other studies.

Sørensen coefficients of similarity give an overall measure of similarity, but all species are weighted equally, so that indicator species carry the same weight as those of broad ecological range and the absence of shared constant species is sometimes compensated for by the presence of several shared species in low constancy classes. This pattern is evident, for example, in woodland communities, where numerous species indicative of woodlands but not of springs are present at low frequencies. They are useful in making comparisons between groups, but the group with the highest similarity coefficient is not necessarily the best fit, especially where constant species are missing.

New samples can be added to an existing ordination in NMS using PC-ORD Version 5.33 without altering the positions of the original points (McCune & Grace 2002). NMS scores were calculated for the German relevés based on the original Irish ordination, and they were plotted on the ordination along with the Irish samples (Fig. 4.2, 4.3 and 4.4 below). The fuzzy clustering programme 'fanny' does not allow new samples to be added to an existing classification.

4.2 Results for Irish Petrifying Spring Communities

4.2.1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades

Eucladium verticillatum-Pellia endiviifolia Tufa Cascades are very similar in species composition to *Adiantion* communities (*e.g.* Deil 1994, Table 4.1), except that *Adiantum capillus-veneris* is absent from my Group 1 samples. The Indicator Species of Group 1 (as determined by ISA), *Eucladium verticillatum, Didymodon tophaceus* and *Pellia endiviifolia* are characteristic of *Adiantion* communities. Both communities colonise steep cliffs irrigated with calcareous water, and bryophytes form an often continuous, tufa-encrusted layer in both. Most Group 1 samples lie outside the narrow biogeographical range of *Adiantum capillus-veneris* in Ireland, except for one sample from the Burren and one from a waterfall in Sligo, both of which are somewhat exposed compared to the typically sheltered habitat of *A. capillus-veneris*. *Samolus valerandi*, constant in *Adiantion* communities, is present, although infrequent, in Group 1 samples.

Group 1 samples come close to Philippi's (1961) *Eucladietum verticillati* community in terms of constant species; *Palustriella commutata* and *Eucladium verticillatum* are present at high frequencies in both. *Aneura pinguis* (IV in the *Eucladietum verticillati* community) is seldom present in my Group 1 samples. Conversely, *Didymodon tophaceus*, frequent in Group 1 samples, was not recorded by Philippi, although *D. fallax* was. The latter species may replace the former in the communities of the Wutachschlucht river valley in the Black Forest, Germany; there is also, perhaps, the possibility of misidentification of these similar species (*D. fallax* has seldom been recorded in *Cratoneurion* communities).

The *Pellio endiviifoliae-Cratoneuretum commutati* Rivola 1982 is similar to Group 1 with regard to the abundance of *Pellia endiviifolia* and *Palustriella commutata*, but has *Eucladium verticillatum* occurring at lower frequencies, while *Brachythecium rivulare* and *Campylium stellatum* are constant (Hadač 1983). These last two species are rare and absent respectively in Group 1 samples.

Oberdorfer's *Cratoneuretum filicino-commutati* has a high similarity coefficient with Group 1 (43%, joint highest with Deil's *Adiantion* communities). There is somewhat less agreement of constants between this community and Group 1, but they share many species in common.

An Irish example of *Adiantion* communities, *Adiantum capillus-veneris* stands from the Burren (Ivimey-Cook & Proctor 1966), shows some agreement in species composition (apart from *A. capillus-veneris*) but contains different species frequencies to my Group 1 samples.

Table 4.1: Phytosociological relationships of *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades (Group 1).

ISA		*Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades (Gr. 1)	*Adiantion* Communitites (Deil 1994)	*Eucladietum verticillati* (Philippi 1965)	*Pellio endiviifoliae-Cratoneuretum commutati* (Hadač 1983)	*Cratoneuretum filicino-commutati* (Oberdorfer 1977)	*Adiantum capillus-veneris* Stands (Ivimey-Cook & Proctor 1966)
	SCS		43%	35%	35%	43%	39%
	n	18	c.500	9	ns	60	10
***	Eucladium verticillatum	V	V	V	II	II	II
**	Pellia endiviifolia	IV	II	II	IV	II	I
	Palustriella commutata	IV	I	V	V	V	I
	Agrostis stolonifera	IV	I	I	III	II	
***	Didymodon tophaceus	III	I				
	Festuca rubra	III					
	Geranium robertianum	II				II	I
	Hedera helix	II	I				I
	Plantago maritima	II					
	Aneura pinguis	I	I	IV		I	
	Bryum pseudotriquetrum	I		II	N1	III	I
	Conocephalum conicum agg.	I	I	I	II	II	I
	Cratoneuron filicinum	I	I	I	I	II	
	Brachythecium rivulare	I			V	II	
	Samolus valerandi	I	IV				
	Adiantum capillus-veneris		V				V
	Campylium stellatum				V	I	
	Didymodon fallax			I			

SCS = Sørensen Coefficient of Similarity
n = number of samples
ns = not stated
N1 = listed in text but omitted from table
ISA = Indicator species analysis; ***p-value <0.001 **p-value <0.01 *p-value <0.5

4.2.2 *Palustriella commutata – Geranium robertianum* Springheads

Equisetum telmateia, *Carex remota* and *Fraxinus excelsior* suggest a link to the *Equiseto telmatejae-Fraxinetum* Oberd. ex Seib. 1987. The first two of these are Indicator Species for Group 2, although they are not constant. There are several other species in common, but the relative proportions differ in the two communities (Table 4.2). *Palustriella commutata*, the dominant species in Group 2, is only occasionally present in the *Equiseto telmatejae-Fraxinetum*.

Similarly, the Group 2 constant species *Geranium robertianum* and *Pellia endiviifolia* are infrequent in that community. The *Equiseto telmatejae-Fraxinetum* forms in the flush below *Palustriella* springs (Oberdorfer 1992), unlike Group 2 samples which occur at the springhead itself, so while there is some overlap of species, the two are not directly equivalent. Sørensen coefficients of similarity show that this is the community to which Group 2 samples are most closely related. However, this results from the fact that both have numerous low-frequency woodland species in common; it is not an accurate reflection of the differences in relation to spring specialists between the two communities.

The *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977 comes closest to matching the constant species of *Palustriella commutata–Geranium robertianum* Springheads. *Palustriella commutata* is ubiquitous in both although woodland species such as *Geranium robertianum* and *Pellia endiviifolia*, characteristic of Group 2, are less frequent in the *Cratoneuretum filicino-commutati*.

In common with the *Pellio endiviifoliae-Cratoneuretum commutati* Rivola 1982 are the Group 2 constants *Palustriella commutata* and *Pellia endiviifolia*. *Campylium stellatum*, a characteristic fen species is constant in that community (Hadač 1983) but absent from my Group 2 samples. Conversely, Group 2 vascular woodland species are not represented in the *Pellio endiviifoliae-Cratoneuretum commutati* Rivola 1982.

The NVC spring communities M37 *Cratoneuron commutatum-Festuca rubra* Springs and M38 *Cratoneuron commutatum-Carex nigra* Springs (Rodwell 1998b) correspond in the constant presence of *Palustriella commutata*, but they have little else in common with Group 2 since they occur in unshaded locations rather than in woodland. The NVC community W7 *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* Woodland is more closely related in terms of shared woodland species but Group 2 spring specialists, such as *Equisetum telmateia, Palustriella commutata, Pellia endiviifolia* and *Eucladium verticillatum,* are scarce in or absent from W7. *Palustriella commutata-Geranium robertianum* Springheads provide evidence that the recognition of a separate woodland type with *Equisetum telmateia* and *Palustriella commutata* is warranted (as surmised within the description of the W7b *Carex remota-Cirsium palustre* sub-community, Rodwell 1998a).

Ivimey-Cook and Proctor's Calcareous Spring Communities of the Burren (1966) overlap broadly in species composition, but have large differences in their respective frequencies. Apart from *Pellia endiviifolia*, the constants in each community are scarce in the other.

Table 4.2: Phytosociological relationships of *Palustriella commutata-Geranium robertianum* Springheads (Group 2).

		Palustriella commutata-Geranium robertianum Springheads (Gr. 2)	*Equiseto telmatejae-Fraxinetum* (Oberdorfer 1992)	*Cratoneuretum filicino-commutati* (Oberdorfer 1977)	*Pellio endiviifoliae-Cratoneuretum commutati* (Hadač 1983)	W7 *Alnus glutinosa-Fraxinus excelsior-Lysmiachia nemorum* woodland (Rodwell 1998a)	M37 *Cratoneuron commutatum-Festuca rubra* (Rodwell 1998b)	M38 *Cratoneuron commutatum-Carex nigra* (Rodwell 1998b)	Calcareous spring communities (Ivimey-Cook & Proctor 1966)
	SCS		55%	44%	31%	48%	32%	29%	40%
ISA	**n**	26	56	60	ns	102	33	26	8
***	Palustriella commutata	V	II	V	V	I	V	V	I
***	Geranium robertianum	IV	II	II		I			I
	Pellia endiviifolia	IV	I	II	IV	I	I	I	V
***	Rubus fruticosus	III	I			II			
*	Equisetum telmateia	III	V	I		I			
	Fraxinus excelsior	III	V			II			
	Agrostis stolonifera	III		II	III		II	II	IV
	Eucladium verticillatum	III		II	II				
**	Carex remota	II	III			II			
**	Hedera helix	II	I			I			
**	Asplenium scolopendrium	II							
*	Chrysosplenium oppositifolium	II				II	II		
	Plagiomnium undulatum	II	IV	I	III	III			II
	Brachypodium sylvaticum	II	IV			I			
	Eupatorium cannabinum	II	III	II		I			I
	Cardamine pratensis	II	III	I		I	III	V	III
	Filipendula ulmaria	II	III			IV			III
	Brachythecium rivulare	II	II	II	V	II	I	II	II
	Cratoneuron filicinum	II	I	II	I		II	IV	V
	Poa trivialis	II	I			III	II	II	II
	Carex sylvatica	I	IV						
	Deschampsia cespitosa	I	III	I		III	II	II	
	Ajuga reptans	I	III	I		I			
	Acer pseudoplatanus	I	III			II			
	Circaea lutetiana	I	III			II			
	Carex flacca	I	II	II			I	II	IV
	Bryum pseudotriquetrum	I	I	III	N1		IV	V	III
	Lysimachia nemorum	I	I			IV			II
	Festuca rubra	I					IV	IV	II
	Juncus articulatus	I					I	III	IV
	Campylium stellatum			I	V			III	II
	Saxifraga aizoides						III		
	Carex nigra						II	V	
	Carex panicea						II	V	II
	Philonotis fontana						II	IV	
	Carex demissa						I	IV	
	Selaginella selaginoides						I	IV	I
	Scorzoneroides autumnalis							V	II

SCS = Sørensen Coefficient of Similarity

n = number of samples

ns = not stated

N1 = listed in text but omitted from table

ISA = Indicator species analysis; ***p-value <0.001 **p-value <0.01 *p-value <0.5

4.2.3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes

The closest match to Group 3 samples is Ivimey-Cook and Proctor's (1966) Calcareous Spring Community from the Burren. The most significant indicator species of Group 3, as well as other constancy class V and IV species, are all represented in that Burren community, although with some differences in frequency (Table 4.3).

Of the continental European communities, the *Pellio endiviifoliae-Cratoneuretum commutati* Rivola 1982 and *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977 share some constant species (*Palustriella commutata* and, in the case of the former community, *Brachythecium rivulare*). The *Equiseto telmatejae-Fraxinetum* Oberd. ex Seib. 1987 shares many Group 3 woodland species and has the highest coefficient of similarity, in spite of agreeing only weakly with constant and indicator species. The closest British communities are the *Cratoneuron filicinum* Community Birse 1980 and M37 *Cratoneuron commutatum-Festuca rubra* Spring Community (Rodwell 1998b).

The disparate nature of the samples contained within *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes makes it unlikely that a close match should be found amongst other described communities. In addition, the stream and flush physiognomy of many samples is different to the spring setting of other studies. The extent of agreement with Ivimey-Cook and Proctor's Calcareous Springs of the Burren is surprising in this context. Group 3 contains only one sample from the Burren (QL070 Keelhilla Waterfall), which itself was quite different in vegetation composition to other Burren samples recorded in my survey.

Table 4.3: Phytosociological relationships of *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes (Group 3).

		Brachythecium rivulare-Platyhypnidium riparioides Tufaceous Streams and Flushes (Gr. 3)	Calcareous spring communities (Ivimey-Cook & Proctor 1966)	*Pellio endiviifoliae-Cratoneuretum commutati* (Hadač 1983)	*Cratoneuretum filicino-commutati* (Oberdorfer 1977)	*Equiseto telmatejae-Fraxinetum* (Oberdorfer 1992)	*Cratoneuron filicinum* Community (Birse 1980)	M37 *Cratoneuron commutatum-Festuca rubra* (Rodwell 1998b)
	SCS		43%	34%	41%	54%	34%	30%
ISA	**n**	29	8	ns	60	56	4	33
***	Brachythecium rivulare	V	II	V	II	II	III	I
	Agrostis stolonifera	V	IV	III	II		I	II
*	Cratoneuron filicinum	IV	V	I	II	I	IV	II
	Palustriella commutata	IV	I	V	V	II	I	V
***	Ranunculus repens	III	II			I		
	Pellia endiviifolia	III	V	IV	II	I	II	I
	Geranium robertianum	III	I		II	II		
	Mentha aquatica	III	I			I		
***	Platyhypnidium riparioides	II	I		I			
*	Nasturtium officinale agg.	II	II					
*	Brachypodium sylvaticum	II				IV		
	Cardamine pratensis	II	III		I	III	III	III
	Filipendula ulmaria	II	III			III		
	Plagiomnium undulatum	II	II	III	I	IV		
	Poa trivialis	II	II			I	IV	II
	Equisetum telmateia	II			I	V		
	Fraxinus excelsior	II				V		
	Carex remota	II				III		
	Chrysosplenium oppositifolium	II					II	II
*	Apium nodiflorum	I						
*	Glyceria notata	I						
	Carex flacca	I	IV		II	II		I
	Juncus articulatus	I	IV				I	I
	Bryum pseudotriquetrum	I	III	N1	III	I	II	IV
	Festuca rubra	I	II				IV	IV
	Campylium stellatum		II	V	I			
	Carex panicea		II					II
	Scorzoneroides autumnalis		II					
	Selaginella selaginoides		I					I
	Carex sylvatica					IV		
	Philonotis fontana						III	II
	Carex nigra						I	II
	Saxifraga aizoides							III
	Carex demissa							I

SCS = Sørensen Coefficient of Similarity
n = number of samples
ns = not stated
N1 = listed in text but omitted from table
ISA = Indicator species analysis; ***p-value <0.001 **p-value <0.01 *p-value <0.5

4.2.4 *Palustriella commutata-Agrostis stolonifera* Springheads

Group 4 samples have much in common with Ivimey-Cook and Proctor's (1966) Calcareous Spring Communities of the Burren, except that *Palustriella commutata* in Group 4 samples is largely replaced by *Cratoneuron filicinum* and *Pellia endiviifolia* in the Burren samples. While several of my groups have affinities with Ivimey-Cook and Proctor's calcareous Burren springs, Group 4 comes closest to that community, with a similarity coefficient of 58%.

In terms of British plant communities, Group 4 samples are intermediate between the NVC communities M37 *Cratoneuron commutatum-Festuca rubra* springs, M38 *Cratoneuron commutatum-Carex nigra* springs and M10 *Carex dioica-Pinguicula vulgaris* mires (Table 4.4). Group 4 samples fall into two subgroups: (1) springhead samples and (2) flushes or diffuse seepages (Chapter 3). The springhead samples in Group 4 match the M37 community very closely, with constant *P. commutata* and *F. rubra.* Both have the same general physiognomy, in spite of the fact that the NVC samples are from higher altitudes. Group 4 flush species, however, are poorly represented in M37. They are to be found in M10 *Carex dioica-Pinguicula vulgaris* mires, but many typical M10 species are absent from or infrequent in Group 4. Within M10, the M10b *Briza media-Primula farinosa* sub-community and M10bi *Cirsium palustre* variant are closer to Group 4 than the overarching M10 community (although *P. farinosa* is absent from Ireland); they match the high-constancy species of Group 4 more closely.

Once again, the *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977 has one of the highest similarity coefficients (41%) and shows a general overlap of species with Group 4.

This group also bears some resemblance to the subassociation *filipenduletosum* of the *Cratoneureto filicinae-Cardaminetum* Maas 1959, with the presence of *Filipendula ulmaria, Equisetum palustre, Equisetum telmateia, Cratoneuron filicinum* and *Brachythecium rivulare*. However, these species are present with low frequencies in Group 4 samples.

Table 4.4: Phytosociological relationships of *Palustriella commutata-Agrostis stolonifera* Springheads (Group 4)

ISA		*Palustriella commutata-Agrostis stolonifera* Springheads (Gr. 4)	Calcareous spring communities (Ivimey-Cook & Proctor 1966)	M37 *Cratoneuron commutatum-Festuca rubra* Spring (Rodwell 1998b)	M38 *Cratoneuron commutatum-Carex nigra* Spring (Rodwell 1998b)	M10 *Carex dioica-Pinguicula vulgaris* mire (Rodwell 1998b)	M10b *Briza media-Primula farinosa* sub-community (Rodwell 1998b)	M10bi *Cirsium palustre* variant (Rodwell 1998b)	*Cratoneuretum filicino-commutati* (Oberdorfer 1977)
	SCS		58%	40%	42%	37%	40%	39%	41%
	n	28	8	33	26	217	55	9	60
**	Agrostis stolonifera	V	IV	II	II	II	III	III	II
	Palustriella commutata	V	I	V	V	II	III	IV	V
	Festuca rubra	V	II	IV	IV	I	I	II	
	Carex flacca	IV	IV	I	II	II	IV	IV	II
	Juncus articulatus	IV	IV	I	III	IV	IV	IV	
	Calliergonella cuspidata	IV	II		II	I	II	V	I
**	Filipendula ulmaria	III	III		II	I	II	IV	
	Cratoneuron filicinum	III	V	II	IV	I	I	III	II
	Bryum pseudotriquetrum	III	III	IV	V	IV	IV	V	III
	Mentha aquatica	III	I						
*	Juncus inflexus	II							
*	Ranunculus flammula	II	I		III	I	II	III	
	Pellia endiviifolia	II	V	I	I	I	II	II	II
	Cardamine pratensis	II	III	III	V	I	II	IV	I
	Carex panicea	II	II	II	V	V	V	V	
	Carex lepidocarpa	II	II	I	I	IV	IV	IV	
	Equisetum palustre	II	I	II	III	II	III	IV	I
	Cirsium palustre	II			III	I	II	V	
	Pinguicula vulgaris	I	II	I		V	IV	V	I
	Angelica sylvestris	I	II			I	II	IV	
	Campylium stellatum	I	II		III	IV	IV	IV	I
	Molinia caerulea	I	II			III	IV	V	I
	Succisa pratensis	I	II			III	IV	V	
	Aneura pinguis	I	I	II	III	IV	IV	IV	I
	Briza media	I	I		II	II	IV	IV	
	Carex hostiana	I	I			IV	V	V	
	Potentilla erecta	I	I		II	III	IV	III	
	Saxifraga aizoides	I		III		I	I		
	Ctenidium molluscum	I		I	III	IV	V	IV	
	Eriophorum angustifolium	I		I	I	IV	IV	III	
	Triglochin palustris	I		I	III	III	IV	V	
	Galium uliginosum	I				I	II	IV	
	Selaginella selaginoides		I	I	IV	III	IV	II	
	Linum catharticum		I		I	II	IV	III	
	Carex dioica			II	II	IV	IV	III	
	Carex nigra			II	V	III	III	IV	
	Carex pulicaris			I	III	IV	IV	IV	
	Parnassia palustris				I	II	III	IV	
	Primula farinosa					II	IV	II	

SCS = Sørensen Coefficient of Similarity

n = number of samples

ISA = Indicator species analysis; ***p-value <0.001 **p-value <0.01 *p-value <0.5

4.2.5 *Schoenus nigricans* Springs

This group conforms to the *Schoenetum nigricantis* (Allorge 1922) Koch 1926 as it occurs in Irish fens and flushes (Ó Críodáin & Doyle 1997). *Schoenus nigricans* is the only character species of the association, lending to it a distinct morphology due to its dominance and tussock-forming habit. Most species, and in particular *Succisa pratensis, Pinguicula vulgaris, Anagallis tenella, Molinia caerulea, Carex panicea, C. lepidocarpa, Campylium stellatum, Scorpidium scorpioides* and *Aneura pinguis,* occur at comparable frequencies in both Group 5 and the *Schoenetum nigricantis* (Table 4.5). (*Drepanocladus revolvens* is present in Ó Críodáin and Doyle's relevés (constancy class II); it may include *Scorpidium cossonii* (syn. *D. revolvens* var. *intermedius*) present in my samples, but this is not explicit in the paper.) Comparing my Group 5 samples with Ó Críodáin and Doyle's *Schoenetum nigricantis* yielded a Sørensen Coefficient of Similarity of 72%; this is the highest coefficient obtained for any of my groups.

Palustriella commutata and *P. falcata* are frequent in Group 5 (55% of samples contain one or both species, with cover up to 55%, Table 3.5, Chapter 3) but are rare in Ó Críodáin and Doyle's data (present in 3% of samples, cover ≤25%) and tufa formation was not reported by those authors. My sampling strategy targeted locations with greatest tufa formation and, as confirmed by the overall results of my field survey, *Palustriella* species thrive in these localised conditions. In addition, in choosing sample locations, I actively sought out points of emergence of spring water; for example, the highest point in a hydrological sequence, or locations from which water was perceived to flow away, albeit very slowly in some *Schoenus*-dominated habitats. It is difficult to pinpoint exact locations where water issues from below ground in fen habitats which are extensive and on almost level ground, but I consider that my samples (and the abundance of tufa and *Palustriella* species) coincide with areas of intense seepage of water from below ground. Thus, in most cases, my Group 5 samples represent springs and seepages within a wider fen context.

Dactylorhiza majalis subsp. *traunsteineroides* is present in two Group 5 samples. Vegetation containing this taxon in Scragh Bog, Co. Westmeath was assigned to the *Schoenetum nigricantis* subassociation *Caricetosum lasiocarpae* (Ó Críodáin & Doyle 1997). However, my Group 5 samples are not a good fit with either this subassociation or any of the others described by Ó Críodáin and Doyle. Those subassociations occur on wet ground with relatively low base levels or on drier, base-rich ground. In contrast, my Group 5 samples are from wet, base-rich habitats.

Table 4.5: Phytosociological relationships of *Schoenus* nigricans Springs (Group 5)

			Schoenus nigricans Springs (Gr. 5)	*Schoenetum nigricantis* (ÓCriodáin & Doyle 1997)	M13 *Schoenus nigricans-Juncus subnodulosus* mire (Rodwell 1998b)	M10 *Carex dioica-Pinguicula vulgaris* mire (Rodwell 1998b)	M10a *C. demissa-J. bulbosus* sub-community (Rodwell 1998b)	M10aiii *Schoenus nigricans* variant (Rodwell 1998b)	*Eriophorum latifolium - Carex hostiana* Ass. (Birks 1973)
		SCS		72%	65%	56%	58%	53%	51%
ISA		**n**	22	108	126	217	143	36	11
***	Schoenus nigricans		V	V	V	I	II	V	V
***	Campylium stellatum		V	IV	IV	IV	V	V	V
***	Molinia caerulea		IV	V	V	III	III	IV	III
***	Ctenidium molluscum		IV	I	II	IV	III	II	II
***	Potentilla erecta		III	III	IV	III	III	II	
***	Scorpidium scorpioides		III	III		II	III	V	V
***	Scorpidium cossonii		III						III
**	Selaginella selaginoides		III	I	I	III	III	III	IV
	Succisa pratensis		III	IV	IV	III	III	III	IV
	Carex panicea		III	III	V	V	V	V	V
	Anagallis tenella		III	II	III				
	Aneura pinguis		III	II	II	IV	III	II	III
	Carex lepidocarpa		III	II	III	IV	II	I	I
	Pinguicula vulgaris		III	II	II	V	V	V	V
	Festuca rubra		III	I	II	I	I		
	Palustriella commutata		III	I	II	II	I	I	I
	Palustriella falcata		III	I					
**	Phragmites australis		II	III	III				
*	Carex pulicaris		II	I	II	IV	III	II	III
	Mentha aquatica		II	III	III				
	Calliergonella cuspidata		II	II	V	I	I	I	
	Bryum pseudotriquetrum		II	I	II	IV	II	I	II
	Carex flacca		II	II	III	II	II	II	IV
	Juncus articulatus		II	I	II	IV	III	II	III
	Juncus subnodulosus		II	I	V				
	Eleocharis quinqueflora		II		I	III	III	III	V
	Eriophorum angustifolium		II	I	I	IV	III	II	I
	Philonotis calcarea		II	I	I				
*	Calluna vulgaris		I	I	I				
*	Drosera rotundifolia		I	I	I	I	II	III	II
*	Pinguicula lusitanica		I	I		I	I	II	II
*	Carex distans		I						
	Carex dioica		I	I	I	IV	III	III	IV
	Carex hostiana		I	I	II	IV	IV	IV	V
	Carex nigra		I	I	II	III	III	III	III
	Cladium mariscus		I	I	II				
	Dactylorhiza majalis subsp. traunsteineroides		I	I					
	Eriophorum latifolium		I	I	II	II	II	III	V
	Triglochin palustris		I	I	I	III	II	II	III
	Erica tetralix		I	I	II	II	III	IV	IV
	Drosera anglica			I		I	I	IV	III
	Carex demissa			I		III	III	III	V
	Blindia acuta					I	I	III	IV

SCS = Sørensen Coefficient of Similarity

n = number of samples

ISA = Indicator species analysis; ***p-value <0.001 **p-value <0.01 *p-value <0.5

There is a lack of consensus over the occurrence of *Juncus subnodulosus* in the *Schoenetum nigricantis* association. Ó Críodáin and Doyle adopt the interpretation of Koch (1926) who assigned *J. subnodulosus*-dominated vegetation to the *Juncetum subnodulosi*. Thus, *J. subnodulosus* is present in only 15% of Ó Críodáin and Doyle's *Schoenetum nigricantis* relevés (cover ≤50%), and this is comparable to Group 5 samples (II, cover 0.5% to 15%). In the British National Vegetation Classification however, the two species are combined in the M13 *Schoenus nigricans-Juncus subnodulosus* mire community which is treated as synonymous with the *Schoenetum nigricantis*. In the M13 community, *J. subnodulosus* is constant and sometimes dominant. *Calliergonella cuspidata* is also constant in the M13 community but of low frequency in Group 5. Thus, Group 5 vegetation has more in common with the *Schoenetum nigricantis* (Allorge 1922) Koch 1926 as interpreted by Ó Críodáin and Doyle than with the M13 *Schoenus nigricans-Juncus subnodulosus* mire community of the NVC.

The M10 *Carex dioica-Pinguicula vulgaris* mire community contains a variant with *Schoenus nigricans* (M10aiii), in which *J. subnodulosus* is absent and *Calliergonella cuspidata* is present at low frequencies. *Scorpidium scorpioides* is prominent in both my Group 5 and the M10aiii *Schoenus nigricans* variant, but absent from M13. However, the high frequencies of *Erica tetralix* and *Drosera anglica* and, to a lesser extent, *Carex demissa* and *Blindia acuta* in the M10aiii *Schoenus nigricans* variant are indicative of less base-rich conditions than in Group 5, where these species are almost entirely absent.

The *Eriophorum latifolium-Carex hostiana* Association (Birks 1973), like Group 5, contains constant *Schoenus nigricans* and *Campylium stellatum*, along with frequent to constant *Pinguicula vulgaris, Selaginella selaginoides, Scorpidium scorpioides* and *S. cossonii*. The gently sloping, water-scoured, stoney flush physiognomy of Birks' association is reminiscent of an ecologically distinctive Group 5 sample from the lower slopes of the Benbulbin Range (QL132 Cormac Reagh's Hole). However, *E. latifolium* was not recorded at this site.

4.2.6 *Carex lepidocarpa* Small Sedge Springs

Of my eight groups, Group 6 comes closest to the M10 *Carex dioica-Pinguicula vulgaris* Mire community (Rodwell 1998b, Sørensen Coefficient of Similarity 58%). Both have comparable frequencies of *Carex lepidocarpa, C. panicea, Eleocharis quinqueflora, Bryum pseudotriquetrum, Campylium stellatum* and *Aneura pinguis* (Table 4.6). *Palustriella commutata*, present in both, is somewhat more frequent in Group 6, along with *Festuca rubra, Anagallis tenella* and *Philonotis calcarea*; the two last-named species are not recorded from M10 communities. On the other hand, *Pinguicula vulgaris, Carex dioica, C. pulicaris, C. hostiana* and *Selaginella selaginoides* are more frequent in the M10 community. Within M10, the M10bi *Cirsium palustre* variant of the *Briza media-Primula farinosa* sub-community is closest to my Group 6 samples (SCS 60%), in spite of the absence of *Primula farinosa* from Ireland. It is in this variant that *Palustriella commutata* becomes most frequent. The authors note that *Anagallis tenella* is poorly represented in their data despite being typical of this kind of vegetation, and there may be a variant containing this species which is not represented within the NVC. My Group 6 samples may represent such a variant; *Anagallis tenella* falls into constancy class III.

In many respects, Group 6 samples lie between the M10 *Carex dioica-Pinguicula vulgaris* mire and the M38 *Cratoneuron commutatum-Carex nigra* spring (Table 4.6). The Turfy Marshes of Upper Teesdale, *Carex panicea-Campylium stellatum* nodum and *Carex nigra-Equisetum palustre* nodum of the Scottish Highlands and the *Cratoneuron-Carex* nodum of the northern Pennines all have affinities with Group 6 samples, although they were, for the most part, recorded at higher altitudes (Pigott 1956, McVean & Ratcliffe 1962, Huntley 1979 and Eddy *et al.* 1969). These syntaxa straddle the M10 and M38 communities in the NVC (Rodwell 1998b).

Of the Irish small-sedge communities reported by Ó Críodáin and Doyle (1994), Group 6 samples come closest to the *Campylio-Caricetum dioicae* Osvald 1925 em. Dierssen 1982. However, the *Campylio-Caricetum dioicae* constants, *Juncus bulbosus* and *Carex demissa*, are scarce and absent (respectively) in Group 6. Conversely, species such as *Festuca rubra, Carex lepidocarpa* and *Bryum pseudotriquetrum*, frequent in Group 6, are absent from or infrequent in the *Campylio-Caricetum dioicae*. Most significantly, *Palustriella commutata* (IV, Group 6) is not reported from the *Campylio-Caricetum dioicae* (Ó Críodáin & Doyle 1994); similarly, *P. falcata* and *Philonotis calcarea* (both II, Group 6) are not listed. On the whole, the composition of Group 6 vegetation is more calcicole in character than the small-sedge communities of those authors (water analysis, discussed in Section 5.2.2, confirms this).

Group 6 also has affinities with the *Molinia*-rich facies of the *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977 (SCS 38%). *Palustriella commutata* is constant in both, and *Pinguicula*

vulgaris, Parnassia palustris, Carex panicea, C. lepidocarpa, Bryum pseudotriquetrum, Campylium stellatum and *Aneura pinguis* are present at similar frequencies. Unlike Group 6, this facies of the *Cratoneuretum filicino-commutati* contains constant *Carex hostiana* and *Primula farinosa* but none of the species *Succisa pratensis, Anagallis tenella, Festuca rubra, Eriophorum angustifolium* or *Carex flacca* (Oberdorfer 1977).

M13 *Schoenus nigricans-Juncus subnodulosus* mire has the highest similarity coefficient with Group 6 (SCS 68%), but the characteristic species of that community, *S. nigricans* and *J. subnodulosus*, are infrequent in my Group 6 samples. The co-occurrence of numerous species of broad ecological range accounts for the high similarity coefficient.

Table 4.6: Phytosociological relationships of *Carex lepidocarpa* Small Sedge Springs (Group 6)

		Carex leipdocarpa Small Sedge Springs (Gr. 6)	M10 *Carex dioica-Pinguicula vulgaris* mire (Rodwell 1998b)	M10bi *B. media-P. farinosa* sub-com, *C. palustre* variant	M38 *Cratoneuron commutatum- Carex nigra* (Rodwell 1998b)	Turfy Marshes (Pigott 1956)	*Carex panicea - Campylium stellatum nodum* (McVean & Ratcliffe 1962)	*Campylio-Caricetum dioicae* (Ó Críodáin & Doyle 1994)	*Molinia*-rich facies of *Cratoneuretum filicino-commutati* Oberd. 1977
	SCS		58%	60%	49%	52%	54%	54%	38%
ISA	**n**	30	217	9	26	N1	18	60	14
***	Succisa pratensis	V	III	V		f	III	III	
	Carex panicea	V	V	V	V	f	V	V	IV
	Festuca rubra	V	I	II	IV	a	II		
***	Carex lepidocarpa	IV	IV	IV	I	a	I	I	IV
***	Calliergonella cuspidata	IV	I	V		f	II	II	II
**	Juncus articulatus	IV	IV	IV	III	a	V	III	
**	Mentha aquatica	IV						III	
*	Bryum pseudotriquetrum	IV	IV	V	V	f	III	I	V
	Carex flacca	IV	II	IV		f	II	I	
	Palustriella commutata	IV	II	IV	V	o	IV		V
***	Equisetum palustre	III	II	IV	III	f	I	I	V
***	Anagallis tenella	III						IV	
**	Eriophorum angustifolium	III	IV	III	I		IV	III	
*	Cardamine pratensis	III	I	IV	V	o	I	I	III
	Aneura pinguis	III	IV	IV	III	o	II	I	III
	Campylium stellatum	III	IV	IV	III	o	V	III	II
	Molinia caerulea	III	III	V		f	II	V	V
	Potentilla erecta	III	III	III	II	r	IV	II	
	Cirsium palustre	III	I	V	III		I		III
***	Triglochin palustris	II	III	V	III	o	I	I	
***	Pedicularis palustris	II	I	II		o	II	III	
**	Carex nigra	II	III	IV	V	a	III	II	
**	Epilobium parviflorum	II							
*	Juncus subnodulosus	II						I	
*	Plagiomnium elatum	II			III				
	Pinguicula vulgaris	II	V	V		f	V	II	II
	Ctenidium molluscum	II	IV	IV	III	f	IV	I	
	Eleocharis quinqueflora	II	III	III		f	IV	II	
	Parnassia palustris	II	II	IV	I	o	I	I	III
	Cratoneuron filicinum	II	I	III	IV		I		II
	Philonotis calcarea	II			III	f	II		IV
	Scorpidium cossonii	II				a	IV		
*	Carex rostrata	I		III	I		I	I	
	Carex hostiana	I	IV	V			III	II	IV
	Carex dioica	I	IV	III	II	f	II	II	
	Carex pulicaris	I	IV	IV	III		IV	III	
	Selaginella selaginoides	I	III	II	IV	o	V	I	
	Carex echinata	I	II	II	II		III	IV	
	Juncus bulbosus	I	II					V	
	Carex demissa		III		IV		IV	V	
	Primula farinosa		II	II		f			V
	Jungermannia atrovirens				II	a			
	Leiocolea bantriensis				II	a			
	Philonotis fontana				IV		I		

SCS = Sørensen Coefficient of Similarity n = number of samples

N1: List with DAFOR scores; d = dominant, a = abundant, f = frequent, o = occasional, r = rare

ISA = Indicator species analysis; ***p-value <0.001 **p-value <0.01 *p-value <0.5

4.2.7 *Palustriella falcata-Carex panicea* Springs

Ivimey-Cook and Proctor's Calcareous Spring Communities of the Burren (1966) correspond closely to my Group 7 samples except that in the former *Cratoneuron filicinum* and *Pellia endiviifolia* replace *Palustriella falcata* and *P. commutata* as constants and *Carex lepidocarpa* and *C. panicea* are less frequent (Table 4.7). 40% of Group 7 samples were recorded in the Burren.

The British M10 *Carex dioica-Pinguicula vulgaris* mire communities have much in common with Group 7 samples; however, *Palustriella falcata* (constant in Group 7) is not distinguished from *P. commutata* in NVC communities. On the whole, compared to my Group 7, M10 communities contain much less *Palustriella* spp and they lack *Philonotis calcarea;* conversely the sedges *Eriophorum angustifolium, Carex dioica, C. pulicaris* and *C. hostiana* are much more frequent in M10 communities. *Pinguicula vulgaris*, constant in M10, is replaced in some Group 7 samples by *P. grandiflora*. Turfy Marshes in Upper Teesdale, which later become encapsulated within M10 mires, show a remarkably similar floristic composition to Group 7 (Pigott 1956). Their physiognomy, though different, perhaps parallels Burren samples; the vegetated hummocks of Upper Teesdale's Turfy Marshes are separated by calcareous gravel rather than by limestone pavement as in the Burren.

Several other British communities also have affinities with Group 7 samples. The *Carex panicea-Campylium stellatum* soligenous mire nodum (McVean and Ratcliffe 1962) corresponds closely, except that, in it, *Carex demissa* mostly replaces *Carex lepidocarpa*. Similarly, M38 *Cratoneuron commutatum-Carex nigra* springs, *Carex nigra-Equisetum palustre* nodum (Huntley 1979) and *Cratoneuron-Carex* nodum (Eddy *et al.* 1969) each show considerable overlap with the floristic composition of Group 7, but the increased presence in those communities of species such as *Philonotis fontana* (rather than *P. calcarea*), *Carex demissa* and *C. nigra* indicates that they are somewhat less calcicolous than my Group 7. (Water analysis was seldom reported in these studies, but pH values provided by Eddy *et al.* (1969) are very much lower than my Group 7 values, Section 5.2.2)

Of the continental European spring communities, Oberdorfer's *Molinia*-rich facies of the *Cratoneuretum filicino-commutati* comes closest, with comparable frequencies of *Carex lepidocarpa, C. panicea, Bryum pseudotriquetrum* and *Philonotis calcarea*. However, *Palustriella falcata* is absent, wheras *P. commutata* is constant.

Table 4.7: Phytosociological relationships of *Palustriella falcata-Carex panicea* Springs (Group 7)

		Palustriella falcata- Carex panicea Springs (Gr. 7)	Calcareous spring communities (Ivimey-Cook & Proctor 1966)	M10 *Carex dioica-Pinguicula vulgaris* mire (Rodwell 1998b)	Turfy Marshes, Upr Teesdale (Pigott 1956)	*Carex panicea - Campylium stellatum nodum* (McVean & Ratcliffe 1962)	M38 *Cratoneuron commutatum-Carex nigra* (Rodwell 1198b)	*Carex nigra - Equisetum palustre* nodum (Huntley 1979)	*Cratoneuron-Carex* nodum (Eddy *et al.* 1969)	*Molinia*-rich facies of *Cratoneuretum filicino-commutati* Oberd. 1977
	SCS		51%	55%	53%	51%	44%	41%	41%	36%
ISA	**n**	20	8	217	N1	18	26	9	20	14
***	Carex panicea	V	II	V	f	V	V	IV	V	IV
***	Palustriella falcata	V	II		o					
	Carex flacca	V	IV	II	f	II	II	III	I	
	Carex lepidocarpa	V	II	IV	a	I	I	II	I	IV
	Agrostis stolonifera	IV	IV	II			II	II	I	I
	Juncus articulatus	IV	IV	IV	a	V	III	IV	III	
	Bryum pseudotriquetrum	IV	III	IV	f	III	V	IV	V	V
**	Philonotis calcarea	III	III		f	II	III		II	IV
	Calliergonella cuspidata	III	II	I	f	II	II	V	II	II
	Festuca rubra	III	II	I	a	II	IV	II	IV	
	Succisa pratensis	III	II	III	f	III		IV		
	Aneura pinguis	III	I	IV	o	II	III	III	IV	III
	Palustriella commutata	III	I	II	o	IV	V	III	V	V
***	Pinguicula grandiflora	II								
**	Briza media	II	I	II		II	II	I	II	
	Anagallis tenella	II	II							
	Campylium stellatum	II	II	IV	o	V	III	I	II	II
	Molinia caerulea	II	II	III	f	II		I		V
	Pinguicula vulgaris	II	II	V	f	V		III	I	II
	Potentilla erecta	II	I	III	I	IV	II	III	II	
	Selaginella selaginoides	II	I	III	o	V	IV	II	IV	
	Ctenidium molluscum	II		IV	f	IV	III		II	
	Parnassia palustris	II		II	o	I	I		I	III
	Cratoneuron filicinum	I	V	I		I	IV		IV	II
	Pellia endiviifolia	I	V	I		I	I		I	
	Prunella vulgaris	I	II	II	f	II	III	III	III	
	Scorzoneroides autumnalis	I	II	I	o	IV	V	V	V	
	Eleocharis quinqueflora	I	I	III	f	IV				
	Equisetum palustre	I	I	II	f	I	III	V	III	V
	Fissidens adianthoides	I	I	II	f	III	III	I	III	V
	Ranunculus flammula	I	I	I	r	II	III	II	IV	
	Carex dioica	I		IV	f	II	II	III	III	
	Carex nigra	I		III	a	III	V	V	V	
	Carex pulicaris	I		IV		IV	III	III	II	
	Eriophorum angustifolium	I		IV		IV	I	V		
	Saxifraga aizoides	I		I	r	II				
	Cardamine pratensis		III	I	o	I	V	III	V	
	Epilobium palustre		II			I	III	II	IV	
	Carex hostiana		I	IV		III		II		IV
	Carex demissa			III		IV	IV	I	IV	
	Deschampsia cespitosa			I		I	II	II	II	
	Philonotis fontana					I	IV	IV	V	

SCS = Sørensen Coefficient of Similarity n = number of samples

N1: List with DAFOR scores; d = dominant, a = abundant, f = frequent, o = occasional, r = rare

ISA = Indicator species analysis; ***p-value <0.001 **p-value <0.01 *p-value <0.5

4.2.8 *Saxifraga aizoides-Seligeria oelandica* Springs

The presence of *Saxifraga aizoides* links this group to a number of published communities (Table 4.8). *Saxifragetum aizoidis* communities (U15 Rodwell 1998c, McVean & Ratcliffe 1962 and Birks 1973) are closest, with constant *S. aizoides* and *Festuca rubra* and with a broad overlap in general species composition. Many of the shared species have broader ecological ranges than the specialist Group 8 habitat type, for example *Linum catharticum, Carex flacca, Aneura pinguis, Ctenidium molluscum, Bryum pseudotriquetrum* and *Calliergonella cuspidata*. Of the Group 8 rare bryophyte species, only *Orthothecium rufescens* is represented amongst the British *Saxifragetum aizoidis* communities; it is constant in this community in the Isle of Skye (Birks 1973). *Seligeria oelandica* is not known from within the geographical range of *Saxifraga aizoides* in Britain and neither *Seligeria* species nor *Hymenostylium recurvirostrum* var. *insigne* is reported from any NVC spring or mire community.

Seligeria oelandica occurs with *Saxifraga aizoides* in Norway (Coker 1983). The very different biogeographical setting of Coker's sample (high latitude and altitude) allows for only a limited comparison; the Norwegian community contains many species which do not occur in Ireland. Species in common with Group 8 samples are *Hymenostylium recurvirostrum, Jungermannia atrovirens* and *Parnassia palustris*. The mosses *Blindia acuta* and *Campylium stellatum* are present in the Norwegian *S. oelandica* community but absent from Group 8.

Leaving aside the rare bryophyte species, Group 8 corresponds to some extent with M37 *Cratoneuron commutatum-Festuca rubra* springs (and the related *Cratoneuron commutatum-Saxifraga aizoides* nodum) and M38 *Cratoneuron commutatum-Carex nigra* springs to some extent (Table 4.8, Rodwell 1998b and McVean & Ratcliffe 1962). With regard to the former (M37), *Saxifraga aizoides, Festuca rubra* and *Palustriella commutata* are constant in both, although other constant species of Group 8 (such as *Sesleria caerulea, Carex flacca, Breutelia chrysocoma, Pellia endiviifolia and Jungermannia atrovirens*) are scarce or absent from M37. M38 shares more species in common with Group 8 than M37 does (and has a higher coefficient of similarity), but there is a greater mismatch of constant species; most notably, *Saxifraga aizoides* is absent from M38, while *Carex nigra* is absent from Group 8 samples.

Group 8 is also related to the M11 *Carex demissa-Saxifraga aizoides* sub-community, M11b *Cratoneuron commutatum-Eleocharis quinqueflora* (SCS 42%) and the M10 *Carex dioica-Pinguicula vulgaris* communities (SCS 42%), which contain similar suites of species to Group 8 but with different frequencies and few shared constant species.

Table 4.8: Phytosociological relationships of *Saxifraga aizoides-Seligeria oelandica* Springs (Gr. 8)

		Saxifraga aizoides - Seligeria oelandica Springs (Gr. 8)	*Saxifragetum aizoidis* (McVean & Ratcliffe 1962)	U15 *Saxifraga aizoides - Alchemilla glabra* Banks (Rodwell 1998c)	*Saxifragetum aizoidis* Ass. (Birks 1973)	Associates of *Seligeria oelandica*, Norway (Coker 1983)	M38 *Cratoneuron commutatum-Carex nigra* (Rodwell 1198b)	M37 *Cratoneuron commutatum-Festuca rubra* (Rodwell 1998b)	*Cratoneuron commutatum - Saxifraga aizoides* nodum (McVean & Ratcliffe 1962)	*Cratoneuretum falcati* (Braun-Blanquet 1978)	*Molinia*-rich facies of *Cratoneuretum filicino-commutati* Oberd. 1977
	SCS		45%	46%	44%	13%	45%	38%	30%	25%	32%
ISA	**n**	13	9	24	7	1	26	33	11	35	14
***	Festuca rubra	V	V	V	V		IV	IV	V		
***	Saxifraga aizoides	V	V	V	V	✓		III	V	III	
**	Carex flacca	V	I	II	III		II	I			
	Pellia endiviifolia	V	III	I			I	I	I		
	Agrostis stolonifera	V	I				II	II	II	V	I
***	Linum catharticum	IV	IV	III			I				
***	Aneura pinguis	IV	I	III	IV		III	II	I	I	III
***	Jungermannia atrovirens	IV	I			✓	II				
***	Sesleria caerulea	IV								I	
**	Cirsium palustre	IV					III				
*	Breutelia chrysocoma	IV	II	I	I			I			
	Ctenidium molluscum	IV	V	IV	IV		III	I			
	Bryum pseudotriquetrum	IV	IV	IV	IV		V	IV	II	II	V
	Calliergonella cuspidata	IV	IV	III	III		II		I		II
	Palustriella commutata	IV	III	III	III		V	V	V	II	V
	Juncus articulatus	IV	I	I			III	I	I		
***	Bellis perennis	III	I				II				
***	Prunella vulgaris	III	I	I			III				
***	Campanula rotundifolia	III		III							
***	Hymenostylium insigne	III									
***	Orthothecium rufescens	III		II	V					I	
***	Seligeria oelandica	III				✓					
***	Seligeria patula	III									
**	Parnassia palustris	III	V	III	III	✓	I				III
**	Fissidens adianthoides	III	III	III	II		III				V
*	Pinguicula vulgaris	III	V	IV	V			I	I		II
	Palustriella falcata	III					I			IV	
***	Alchemilla glabra	II	V	V	V		I	I	I		
***	Gymnostomum aeruginosum	II			II		I	I			
***	Hymenostylium recurvirostrum	II			I	✓		I			I
**	Tussilago farfara	II	I	I				I	I	II	
*	Deschampsia cespitosa	II	V	V	V		II	II	IV	V	III
*	Riccardia chamedryfolia	II									
	Selaginella selaginoides	II	V	V	V		IV	I	I		
	Cratoneuron filicinum	II	II	I			IV	II			II
	Carex lepidocarpa	II	I	II	I		I	I			IV
	Carex panicea	II		I	III		V	II	II	I	IV
	Philonotis calcarea	II					III			IV	IV

Continued below...

Table 4.8 (*contd*): Phytosociological relationships of *Saxifraga aizoides-Seligeria oelandica* Springs (Group 8)

		Saxifraga aizoides - Seligeria oelandica Springs (Gr. 8)	*Saxifragetum aizoidis* (McVean & Ratcliffe 1962)	U15 *Saxifraga aizoides - Alchemilla glabra* Banks (Rodwell 1998c)	*Saxifragetum aizoidis* Ass. (Birks 1973)	Associates of *Seligeria oelandica*, Norway (Coker 1983)	M38 *Cratoneuron commutatum-Carex nigra* (Rodwell 1198b)	M37 *Cratoneuron commutatum-Festuca rubra* (Rodwell 1998b)	*Cratoneuron commutatum - Saxifraga aizoides* nodum (McVean & Ratcliffe 1962)	*Cratoneuretum falcati* (Braun-Blanquet 1978)	*Molinia*-rich facies of *Cratoneuretum filicino-commutati* Oberd. 1977
	SCS		45%	46%	44%	13%	45%	38%	30%	25%	32%
ISA	**n**	13	9	24	7	1	26	33	11	35	14
	Carex pulicaris	I	III	IV	IV		III	I	I		
	Preissia quadrata	I	III	III	IV						
	Cystopteris fragilis	I	II	II	IV						
	Molinia caerulea	I									V
	Saxifraga oppositifolia		V	V	V	✓					
	Thalictrum alpinum		III	IV	III			I	I		
	Blindia acuta		III	III	V	✓		I			
	Campylium stellatum		II	II	I	✓	III				II
	Carex nigra						V	II	II		
	Arabis soyeri ssp. subcoriacea									V	IV
	Saxifraga stellaris									IV	

SCS = Sørensen Coefficient of Similarity
n = number of samples
ISA = Indicator species analysis; ***p-value <0.001 **p-value <0.01 *p-value <0.5

Saxifraga aizoides and *Palustriella falcata* are indicative of Alpine *Cratoneuretum falcati* communities (*e.g.* Braun-Blanquet 1978), although, of course, characteristic species of the alpine community such as *Arabis soyeri* ssp. *subcoriacea* and *Aster bellidiastrum* are absent from Ireland. Species in common are *Tussilago farfara, Agrostis stolonifera, Deschampsia cespitosa, Palustriella commutata, Philonotis calcarea* and *Bryum pseudotriquetrum* (SCS 25%, Table 4.8). The *Molinia*-rich facies of the *Cratoneuretum filicino-commutati* (Oberdorfer 1977) yields a slightly higher similarity coefficient of 32%, although *Saxifraga aizoides* is absent from that community and my other Group 8 constant species are poorly represented.

4.3 German petrifying spring relevés

4.3.1 Sites

Ten relevés were recorded from the Swabian Alps in July 2012, at Urach Waterfall, Güterstein, Talheim, Dießen, Glatt and Wimsen (Fig. 4.1 above).

Urach Waterfall (Photo 4.1) consists of an impressive vertical tufa cascade, some tens of metres high, over which the water spills. It levels out at the base into a flushed area of both cascade and stream crust tufa (Photo 4.2) and eventually forms a small tufa-lined stream on the almost level ground below (Photo 4.3).

At nearby Güterstein, cascade tufa is deposited on a steep hillside. Dry tufa at the spring head (Photo 4.4) indicates where spring water formerly emerged; this is circumvented by the present route of flowing water. Much of this tufa was deposited on the shoots of *Bryum pseudotriquetrum* (Photo 4.5); 'petrified' *B. pseudotriquetrum* was not found on this scale in Irish springs. Kuhn noted that *Palustriella commutata* and *Bryum pseudotriquetrum* were jointly dominant in lime-rich spring water at Güterstein. Spring water gives rise to a tufa-forming flush on the wooded hillside below the springhead (Photo 4.6).

Talheim contains woodland springheads with *Palustriella commutata* and *Cratoneuron filicinum* tufa cascades (Photo 4.7). A small stream flows through pools impounded by dams with *Cratoneuron filicinum* and *Brachythecium rivulare* (Photo 4.8). This spring water feeds into the River Steinlach which flows northwards to Tübingen and joins the Neckar River. Kuhn (1937) referred to the upper River Steinlach as an example of the spring streams in which he had recorded the *Hypnum commutatum-Cratoneuron filicinum* Community.

Dießen contains a remarkable tufa structure known locally in German as 'Kalkrinne' or 'Tuffsteinrinne', a lime or tufa channel, and variously referred to in English as a tufa catwalk, self-built canal or lobe-top terrace (Pentecost 2005, Pedley & Rogerson 2010; see Photos 4.9 to 4.11, and also Photos 6.44 to 6.47 from Pamukkale, Turkey). A small channel of water, flowing swiftly downhill, deposits tufa most rapidly along its margins, so that the flowing water becomes confined within a narrow, central groove. Over time, this builds up vertically forming an aqueduct which is raised above the surrounding ground surface. At Dießen, the channel is approximately 1m above the adjacent land surface. The tufa lip on either side of the water channel is lined with a narrow, almost continuous strip of *Palustriella commutata*. There are small, intermittent clumps of *Cratoneuron filicinum, Platyhypnidium riparioides, Bryum pseudotriquetrum, Brachythecium rivulare*, as well as occasional shoots of grasses such as *Agrostis stolonifera, Poa*

trivialis and *Festuca rubra*. This is the only unshaded site surveyed in Germany during the present study.

A site near Glatt on a wooded hillside consists of *Palustriella commutata*-dominated springhead tufa cascades with *Equisetum telmateia* and *Eupatorium cannabinum* (Photo 4.12).

At Wimsen, a shallow river trickles over tufa dams with *Cratoneuron filicinum* and *Brachythecium rivulare* (Photos 4.13 and 4.14). *Nasturtium officinale* agg. and *Berula erecta* grow on tufa in shallow water. Filamentous green algae at this site (as well as at Urach, Talheim and Glatt) suggest that the spring water might contain elevated levels of macronutrients.

4.3.2 Floristics

As with Irish samples, bryophytes dominate the vegetation recorded in German (Swabian) petrifying springs during the present study. *Palustriella commutata, Cratoneuron filicinum* and *Brachythecium rivulare* are the most frequently occurring species in the German relevés (all constancy class IV, Table 4.9). *P. commutata* is the most abundant species, with a mean cover value of 33%. The other bryophyte species recorded were *Bryum pseudotriquetrum, Platyhypnidium riparioides, Eucladium verticillatum, Hygrohypnum luridum, Plagiomnium undulatum* and *Conocephalum conicum* agg. *Didymodon tophaceus* was present at one site, but not within a relevé.

Vascular plants make a smaller contribution to overall ground cover than bryophytes, but they are more diverse in the range of species present. *Geranium robertianum* is the most frequent species (constancy class III), although present in small quantities (mean cover 0.5%). *Acer pseudoplatanus* (seedlings), *Agrostis stolonifera, Poa trivialis* and *Brachypodium sylvaticum* are occasional (constancy class II). *Lunaria rediviva* and *Chrysosplenium alternifolium*, both absent from Ireland, each occur in two samples. *Alliaria petiolata*, *Berula erecta* and *Scrophularia umbrosa*, present in Ireland but not recorded in Irish petrifying spring relevés, are in one German sample each.

Most samples were recorded in woodland. Overhead canopy was present in 70% of relevés, ranging from 45% to 95% cover. Two samples (20%) were in an open area surrounded by woodland and were lightly shaded by nearby trees. Only one sample (Dießen) was entirely unshaded. The wooded character of most sites is reflected in the presence of species such as *Geranium robertianum, Brachypodium sylvaticum* and *Equisetum telmateia* as well as seedlings of *Acer pseudoplatanus* and *Fraxinus excelsior.*

Table 4.9: Species recorded in German (Swabian) relevés (n=10, all species recorded are listed below). Roman numerals are frequency of presence in relevés (I = up to 20%, II = 21% to 40%, III = 41% to 60%, IV = 61% to 80% and V = 81% to 100%).

Species	Frequency	Mean % Cover	Min % Cover	Max % Cover
Palustriella commutata	IV	33	10	75
Cratoneuron filicinum	IV	11	1	65
Brachythecium rivulare	IV	3	0.5	5
Geranium robertianum	III	0.5	0.1	3
Acer pseudoplatanus	II	0.2	0.1	2
Agrostis stolonifera	II	1	0.5	3
Brachypodium sylvaticum	II	0.4	0.1	3
Bryum pseudotriquetrum	II	0.2	0.5	1
Platyhypnidium riparioides	II	1	1	5
Poa trivialis	II	1	0.5	3
Alliaria petiolata	I	0.1	1	1
Asplenium scolopendrium	I	4	15	20
Berula erecta	I	0.1	1	1
Carex flacca	I	0.1	0.5	0.5
Chrysosplenium alternifolium	I	0.2	0.1	2
Conocephalum conicum agg.	I	0.5	5	5
Equisetum telmateia	I	0.1	0.5	0.5
Eucladium verticillatum	I	0.1	0.5	0.5
Eupatorium cannabinum	I	3	30	30
Festuca rubra	I	0.1	0.5	0.5
Fraxinus excelsior	I	<0.1	0.1	0.1
Hygrohypnum luridum	I	4	40	40
Lunaria rediviva	I	2	10	10
Nasturtium officinale agg.	I	0.5	5	5
Plagiomnium undulatum	I	0.1	0.5	0.5
Scrophularia umbrosa	I	0.3	3	3

Comparison to Kuhn (1937)

In the tufa-forming springs and waterfalls at Urach and Güterstein, Kuhn (1937) recorded *Palustriella commutata, Cratoneuron filicinum, Platyhypnidium riparioides, Bryum pseudotriquetrum, Hymenostylium recurvirostrum* and *Conocephalum conicum*. With the exception of *Hymenostylium recurvirostrum*, these species were refound. *H. recurvirostrum* may still be present at Urach Waterfall (where Kuhn recorded it) but the height and steep slope make much of the tufa-forming surface inaccessible. However, one of the most abundant species recorded in 2012, *Hygrohypnum luridum*, was not listed by Kuhn, suggesting that changes in the vegetation may have taken place in the intervening 75 years. Two additional bryophyte species were found at Güterstein in 2012, *Eucladium verticillatum* and *Didymodon tophaceus,* neither of which was reported in the 1937 survey. Both occupy small areas compared to the dominant *P. commutata*.

Kuhn also makes some brief references to the vegetation of spring streams at other locations in the region. The most ecologically distinctive species recorded in these were *Palustriella commutata, Cratoneuron filicinum* and *Platyhypnidium riparioides*. These species were refound in 2012 in springheads and small streams in the same region, for example, at Talheim and Dießen.

4.3.3 Environmental Variables

Tufa cascades are the predominant form of deposition, occurring in 80% of samples and occupying 71% of ground surface overall (Table 4.10 below). Stream crust tufa is occasional, occupying 16.5% of ground surface, and tufa dams (present in two samples) cover 2.5% of ground surface.

Flowing or trickling water is present in most samples (80%), occupying 5% to 100% of sample area. Dripping water and pools are scarce, occupying 1% and 3% of ground surface respectively.

All samples are on sloping ground, ranging from 5° to 80° with a mean of 43°. Altitudes ranged from 430m to 690m above sea level.

Table 4.10: Environmental variables (mean values) in German (Swabian) relevés and in Irish petrifying spring communities. % values are for surface area cover.

	Germany	Gr. 1	Gr. 2	Gr. 3	Gr. 4	Gr. 5	Gr. 6	Gr. 7	Gr. 8
n	10	18	26	29	28	22	30	20	13
Slope °	43	70	36	27	26	5	5	12	53
Altitude m	590	89	125	114	117	65	71	112	243
Canopy cover %	49	33	51	50	9	0	0	0	1
Tufa %									
Cascade tufa	71.0	88.6	69.6	58.6	36.0	0.0	0.0	11.5	9.2
Stream crust tufa	16.5	5.8	0.0	6.9	2.0	0.9	0.4	12.7	32.7
Tufa dams	2.5	0.0	1.9	0.7	0.0	0.0	0.0	0.0	0.0
Paludal tufa	0.0	0.0	19.8	8.6	38.1	58.3	50.7	35.1	18.2
Other tufa	10.0	0.6	5.2	8.1	4.0	3.6	3.7	6.9	0.0
Non-tufa	0.0	5.0	3.5	17.1	19.9	37.2	45.2	33.8	39.9
Total	100	100	100	100	100	100	100	100	100
Water %									
Flowing / trickling	38.0	13.5	8.4	37.0	12.2	2.1	5.7	15.8	8.1
Dripping	1.2	17.6	6.6	1.1	2.8	0.0	0.0	0.3	12.3
Pools	2.5	0.6	3.4	4.1	5.3	18.8	11.3	11.3	0.5
Damp	54.8	60.8	81.3	51.6	74.9	75.4	82.1	59.6	73.8
Dry	3.5	7.6	0.3	6.2	4.8	3.7	1.0	13.2	5.4

4.3.4 Comparison to Irish Fuzzy Cluster Groups

The woodland situation of most German samples suggests they are likely to have most in common with Group 2 *Palustriella commutata-Geranium robertianum* Springheads and Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes, compared with other Irish groups. Their position on the NMS ordination confirms this (Figs. 4.2, 4.3 and 4.4); all German samples fall within (or close to) the areas occupied by Groups 2 and 3. Samples with the highest proportion of *Palustriella commutata* (at least five times more cover by *P. commutata* than by *Cratoneuron filicinum*) fall closest, on balance, to Group 2. Where *C. filicinum* is relatively more abundant (*i.e.* occupying at least half the area of *P. commutata*), samples lie closer to Group 3.

None of the German samples appears as an outlier on the ordination; the shared bryophyte species create strong affinities. Species recorded in German but not Irish relevés (*Lunaria rediviva*, *Chrysosplenium alternifolium*, *Alliaria petiolata*, *Berula erecta* and *Scrophularia umbrosa*) were omitted from the NMS analysis, as all species present in fewer than four samples were excluded from the original ordination (Chapter 3). None of the above-listed species was present in more than two German relevés and all had low cover values (≤3% cover, except for *L. rediviva* at 10% cover in two relevés). None is typical of *Cratoneurion* vegetation, although *C. alternifolium* appears infrequently as a companion species (*e.g.* Oberdorfer 1977).

Combined as a single group, the German relevés come closest to Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes with respect to species frequencies (Table 4.11 below); they have the highest Sørensen coefficient of similarity with Group 3 and *Cratoneuron filicinum* and *Brachythecium rivulare* are frequent in both. Both of these species are statistically significant indicators of Group 3, as is *Platyhypnidium riparioides,* which is present in both German and Group 3 samples with similar frequency.

Hydrological characteristics of the German relevés match Group 3 very closely, with a predominance of flowing or trickling water over pools and dripping water. The tufa-forming characteristics of the German relevés are somewhat similar to Group 3, as well as to Group 2 *Palustriella commutata-Geranium robertianum* Springheads and Group 1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades with abundant cascade tufa, although the high value for German stream crust tufa is not matched in any of these groups. The absence of paludal tufa from the German samples sets them apart from all but Group 2 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades. German samples are at higher altitudes than any Irish samples but show no similarities with the highest altitude Irish samples (Group 8); this could be due to the Massenerhebung effect, where altitudinal zonation of vegetation varies with the scale of the mountain range (Grubb 1971).

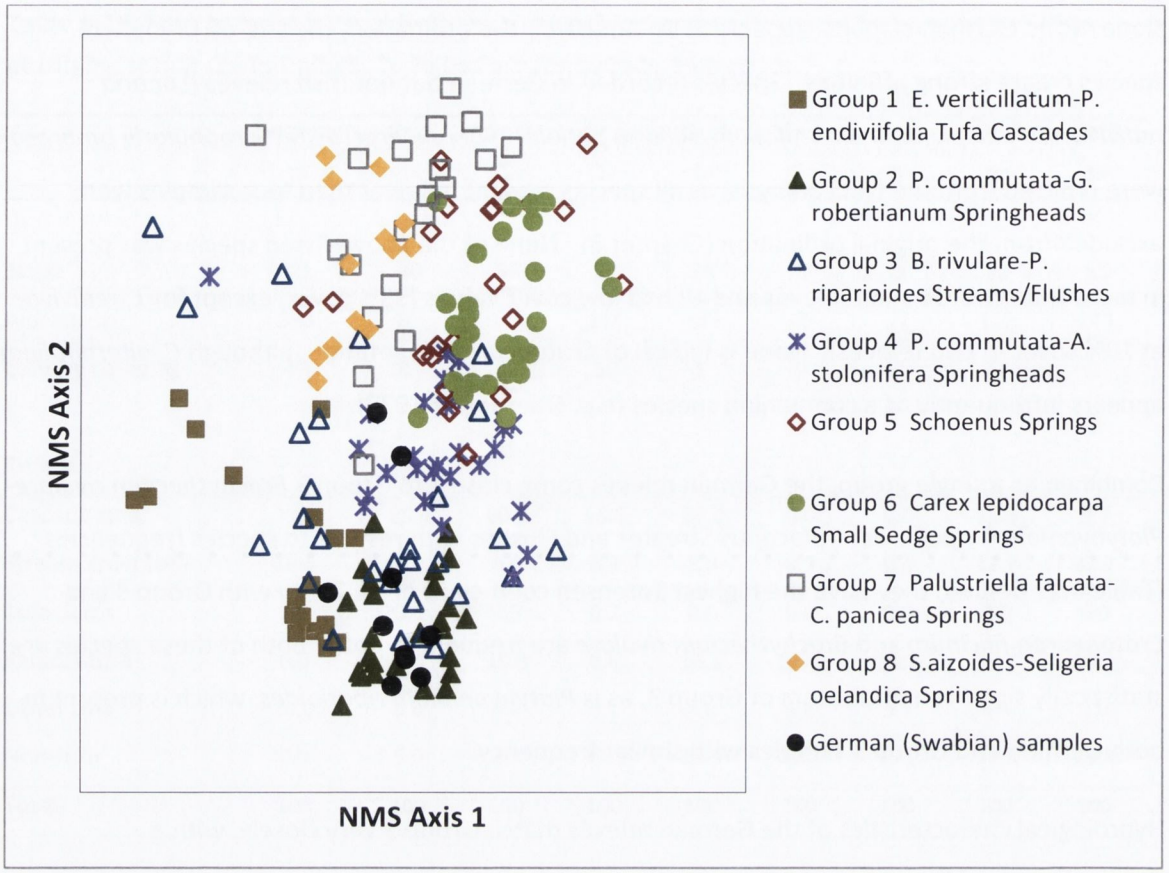


Fig. 4.2: German (Swabian) samples overlaid on original NMS ordination of Irish samples (Section 3.3.1). (Variance (r^2) values of axes: Axis 1 = 0.216 Axis 2 = 0.303).

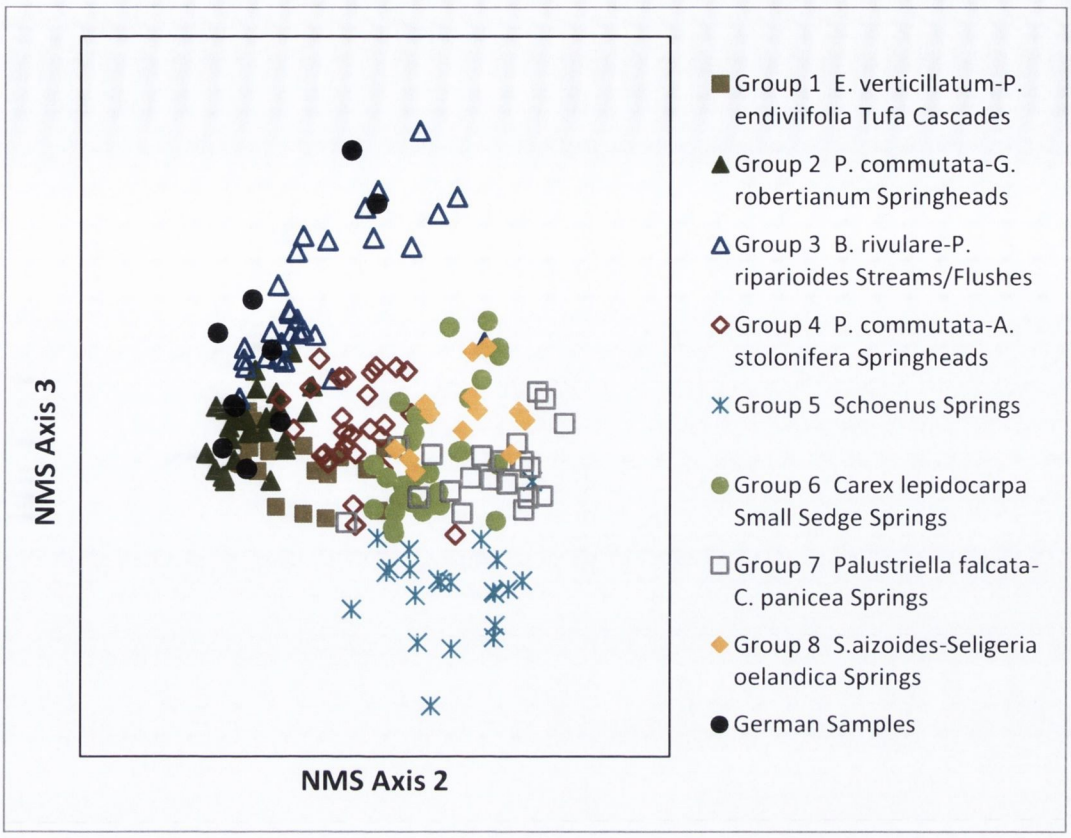


Fig. 4.3: German (Swabian) samples overlaid on NMS ordination of Irish samples (Axes 2 & 3).

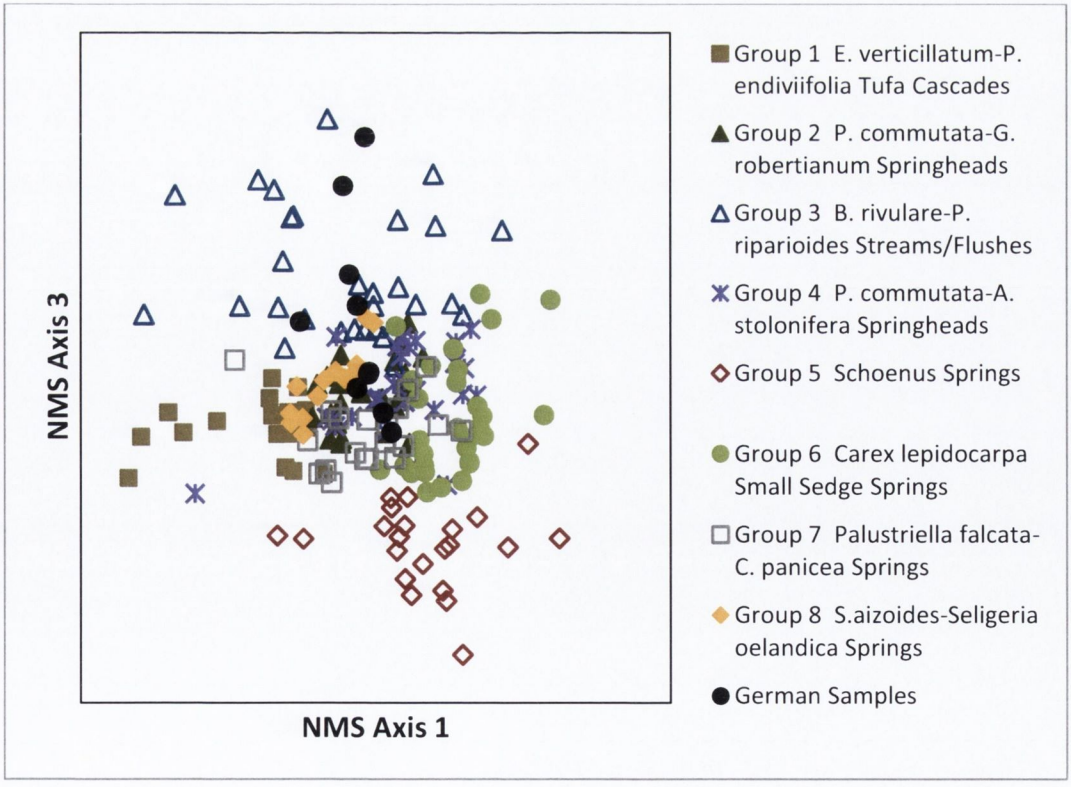


Fig. 4.4: German (Swabian) samples overlaid on NMS ordination of Irish samples (Axes 1 & 3).
Variance (r^2) values of axes: Axis 1 = 0.216 Axis 2 = 0.303 Axis 3 = 0.268

Table 4.11: Species recorded in German relevés compared with Group 2 *Palustriella commutata-Geranium robertianum* Springheads and Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes (and all Irish data). Roman numerals are frequency of occurrence; numbers are mean % cover values. SCS = Sørensen Coefficient of Similarity

Species	**German Relevés**		**Irish Group 3**		**Irish Group 2**		**All Irish**
SCS			52%		42%		
n	10		29		26		186
Palustriella commutata	IV	33	IV	8	V	61	IV
Cratoneuron filicinum	IV	11	IV	5	II	2	II
Brachythecium rivulare	IV	3	V	4	II	1	II
Geranium robertianum	III	0.5	III	1	IV	4	II
Acer pseudoplatanus	II	0.2	I	<0.1	I	0.1	I
Agrostis stolonifera	II	1	V	5	III	3	IV
Brachypodium sylvaticum	II	0.4	II	1	II	1	I
Bryum pseudotriquetrum	II	0.2	I	2	I	0.2	II
Platyhypnidium riparioides	II	1	II	6	I	1	I
Poa trivialis	II	1	II	0.2	II	0.2	I
Alliaria petiolata	I	0.1					
Asplenium scolopendrium	I	4	I	0.2	II	1	I
Berula erecta	I	0.1					
Carex flacca	I	0.1	I	0.2	I	1	III
Chrysosplenium alternifolium	I	0.2					
Conocephalum conicum agg.	I	0.5	I	0.3	I	2	I
Equisetum telmateia	I	0.1	II	5	III	2	I
Eucladium verticillatum	I	0.1	I	0.1	III	1	
Eupatorium cannabinum	I	3	I	0.2	II	4	II
Festuca rubra	I	0.1	I	0.3	I	0.2	III
Fraxinus excelsior	I	<0.1	II	0.4	III	0.4	II
Hygrohypnum luridum	I	4					I
Lunaria rediviva	I	2					
Nasturtium officinale agg.	I	0.5	II	5	I	0.2	I
Plagiomnium undulatum	I	0.1	II	1	II	0.1	I
Scrophularia umbrosa	I	0.3					

4.4 Discussion

In the broadest sense, Irish petrifying springs have greater affinities with the *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977, including the *Molinia*-rich facies, than with any other established community of petrifying springs. Clearly, however, there is a great deal of variation within the habitat which invites refinement to a more detailed level of community analysis. My groups provide a more comprehensive description of lowland petrifying spring habitats as they occur in western Europe. These communities are not represented in the NVC, which deals only with upland petrifying springs in Scotland and the north of England, nor are they adequately described in continental Europe, although they fit broadly under the umbrella of Oberdorfer's *Cratoneuretum filicino-commutati*.

Of my eight communities, Groups 1, 2 and 3 bear the closest relationship to the *Cratoneuretum filicino-commutati*; but they also have affinities with *Adiantion* communities (*e.g.* Deil 1994) and the woodland *Equiseto telmatejae-Fraxinetum* Oberd. ex Seib. 1987. Groups 5, 6 and 7 on the other hand, have more in common with soligenous small-sedge fen communities, for example M10 *Carex dioica-Pinguicula vulgaris* mires, as well M38 *Cratoneuron commutatum-Carex nigra* springs and *Schoenus*-rich communities such as the *Schoenetum nigricantis* (*sensu* Ó Críodáin & Doyle 1997). Group 4 lies between these two extremes and is most closely related to Ivimey-Cook and Proctor's Calcareous Springs of the Burren. Group 8, with its distinctive species-rich montane vegetation, sits amongst U15 *Saxifraga aizoides-Alchemilla glabra* banks, M37 *Cratoneuron commutatum-Festuca rubra* springs and M38 *Cratoneuron commutatum-Carex nigra* springs.

The level of detail in the published studies varies in both the number of species and the geographical scale of the study. Both the *Cratoneuretum filicino-commutati* and Calcareous Spring Communities of the Burren consist of concise lists of some of the most frequently occurring petrifying spring species (the former comprises 60 samples from a wide geographical area in central Europe and the latter contains only 8 samples recorded within the Burren, Oberdorfer 1977 and Ivimey-Cook and Proctor 1966). The only constant species in the *Cratoneuretum filicino-commutati* is *Palustriella commutata*; next most frequent is *Bryum pseudotriquetrum* in class III. Constant species in Calcareous Spring Communities of the Burren are *Agrostis stolonifera, Juncus articulatus, Cratoneuron filicinum* and *Pellia endiviifolia*, all abundant in my data set. It therefore comes as no surprise that these two communities show affinities to several of my groups.

However, my groups provide a more detailed level of analysis; each embodies important ecological characteristics of petrifying springs that are not represented, for the most part, in earlier community descriptions. Clearly, the relationships both within petrifying spring

communities and between these and other related communities are complex; numerous environmental gradients contribute to an interconnected set of vegetation types that cannot readily be explained in a small number of dimensions. In this context, a variety of solutions might usefully contribute to understanding the relationships between my groups and other communities.

I consider that my Irish petrifying spring communities bear the following relationships to other published community descriptions:

Group 1: *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades

Eucladium verticillatum-Pellia endiviifolia Tufa Cascades represent a link between *Cratoneurion* and *Adiantion* communities. In the traditional phytosociological arrangement, they are more logically placed in the *Cratoneurion* alliance as they lack *Adiantum capillus-veneris* and contain much more *Palustriella commutata* than is typical of *Adiantion* communities. They are similar to the *Eucladietum verticillati* (*sensu* Philippi 1965); there is no equivalent community in the NVC.

Group 2: *Palustriella commutata-Geranium robertianum* Springheads & Group 3: *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes

Palustriella commutata-Geranium robertianum Springheads and *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes are sub-associations within the *Equiseto telmatejae-Fraxinetum*, representing respectively, in their most typical forms, the point of emergence of water and the associated water course that ensues. In terms of the NVC, they represent springhead and flush sub-communities within W7 *Alnus glutinosa-Fraxinus excelsior-Lysimachia* nemorum Woodlands.

Group 4: *Palustriella commutata-Agrostis stolonifera* Springheads

Palustriella commutata-Agrostis stolonifera Springheads are a community of lowland, unshaded petrifying springs and flushes, which lack the distinctive characteristics of the other groups. They represent the unshaded, Atlantic facies of the *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977. They are the lowland equivalents of the NVC M37 *Cratoneuron commutatum-Festuca rubra* Springs and M38 *Cratoneuron commutatum-Carex nigra* Springs.

Group 5: *Schoenus* Springs

Schoenus Springs fall within the *Schoenetum nigricantis* (*sensu* Ó Críodáin & Doyle 1997); they represent highly calcareous springs and seepages within that habitat. They lack clear affinities with NVC communities.

Group 6: *Carex lepidocarpa* Small Sedge Springs & Group 7: *Carex panicea-Palustriella falcata* Springs

Carex lepidocarpa Small Sedge Springs and *Carex panicea-Palustriella falcata* Springs lie at the alkaline extreme of the small-sedge communities previously recorded in Ireland by Ó Críodáin & Doyle (1994); Group 7 reaches its fullest expression in the Burren. Both are transitional between *Cratoneurion* petrifying springs and *Caricion davallianae* fen communities. In terms of the NVC, they represent highly calcareous sub-communities within M10 *Pinguicula vulgaris-Carex dioica* Mires.

Group 8: *Saxifraga aizoides-Seligeria oelandica* Springs

Saxifraga aizoides-Seligeria oelandica Springs form a new sub-community within the British *Saxifragetum aizoidis*. They are related to the Scandinavian community recorded by Coker (1983) but differ in their associated species due to the very different geographical and environmental setting.

German (Swabian) Samples

The German relevés recorded in this study correspond to Kuhn's *Hypnum commutatum-Cratoneuron filicinum* and to Oberdorfer's *Cratoneuretum filicino-commutati*. They also match Irish samples closely, as depicted on NMS ordinations. Several characteristic bryophyte species are shared in common, even though there are some differences in the vascular plant complement. Overall, they have most in common with Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes, in terms of floristics, tufa type and hydrological characteristics. Although recorded at higher altitudes, the German relevés correspond to lowland Irish petrifying springs sites, rather than upland (Benbulbin) sites, probably due to the Massenerhebung effect. Oberdorfer (1977) noted that the *Cratoneuretum filicino-commutati* is mostly montane and rare in lowlands in Germany; this does not hold true for Ireland, where it is found down to sea level. An unusual feature of the German sites was the presence of a large tufa cascade, now inactive, formed in association with *Bryum pseudotriquetrum*; this species has not been found to be implicated in the formation of massive deposits in Irish petrifying springs.



Photo 4.1: Massive tufa cascade at Urach Waterfall. *Palustriella commutata* and *Hygrohypnum luridum* are abundant in the spray zone (July 2012).



Photo 4.2: Tufa cascade, with *Palustriella commutata* and filamentous algae, and stream crust tufa below the cascade, at the base of Urach Waterfall (July 2012).



Photo 4.3: Tufaceous stream below Urach Waterfall (July 2012).



Photo 4.4: Dry, inactive tufa at the spring head at Güterstein. In the foreground, *Palustriella commutata* flourishes on actively forming tufa (July 2012).



Photo 4.5: Detail of dry tufa at Güterstein (July 2012). The form of *Bryum pseudotriquetrum* shoots, on which the tufa was precipitated, is replicated in its structure.



Photo 4.6: Tufa-forming woodland flush below Güterstein Waterfall (July 2012). *Palustriella commutata* is the dominant bryophyte within the relevé; small amounts of *Cratoneuron filicinum* and *Brachythecium rivulare* are also present. *Lunaria rediviva* is abundant along the margins of the flush.



Photo 4.7: Spring head tufa cascade at Talheim, which is dry in places. *Cratoneuron filicinum* is abundant; *Palustriella commutata* and *Eucladium verticillatum* occupy smaller areas where the tufa is damp (July 2012).



Photo 4.8: Stream with tufa dams impounding pools at Tallheim. *Cratoneuron filicinum* and *Brachythecium rivulare* grow on the dams (July 2012).



Photo 4.9: Dießen 'Kalkrinne' runs down a steep hillside and continues for some distance after swinging to the side on the lower portion of the slope (July 2012).



Photo 4.10: The tufa channel at Dießen is raised about a metre above the adjacent ground surface. Tall herbaceous wetland vegetation flanks the tufa structure (July 2012).



Photo 4.11: Detail of the tufa channel at Dießen; *Palustriella commutata* colonises a narrow band of damp tufa beside the flowing water, along with grasses such as *Agrostis stolonifera* (July 2012).



Photo 4.12: Springhead tufa cascade at Glatt with *Palustriella commutata* and *Eupatorium cannabinum* (July 2012).



Photo 4.13: River with tufa dams colonised by *Cratoneuron filicinum* and *Brachythecium rivulare* at Wimsen (July 2012).



Photo 4.14: Detail of tufa dam at Wimsen, with *Nasturtium officinale* agg. (above dam), *Berula erecta* (below dam), *Cratoneuron filicinum* and filamentous green algae (both on the dam) (July 2012).

5. Chemical Composition of Spring Water

5.0 Introduction

The chemical composition of spring water determines its tufa-forming capacity and influences the range of species that can colonise the ground it irrigates. Numerous studies have focused on the chemical processes involved in tufa precipitation (*e.g.* Pentecost 1978, 1996, 2005, Rainey & Jones 2007, 2009, Shiraishi *et al.* 2008, Pedley *et al.* 2009, Manzo *et al.* 2012, Zhang *et al.* 2001). The present study deals primarily with water chemistry in relation to habitat types and plant communities, rather than with the tufa deposition process.

Three studies of the chemical composition of tufa-depositing waters were selected for detailed comparison with the overall chemical composition of Irish petrifying spring waters. Firstly, Pentecost (2005) provided a review of tufa-forming (meteogene) spring water analysis, which gives a comprehensive overview of the range of values for the main chemical parameters for petrifying springs across a very wide range of geographical settings in Europe and N. America. Secondly, data were extracted from Arenas *et al.* (2014) on the composition of waters at tufa cascades colonised by bryophytes on the River Piedra located in the Iberian Range, north-east Spain. This detailed study, conducted over a thirteen-year period, reduces the impact of temporal fluctuations. It investigated conditions in different sedimentary facies: 'Facies C: stepped waterfalls and small falls with bryophytes and algae' was chosen as being very similar in vegetation and deposition type to the tufa cascades in Irish petrifying springs. Similar findings to those of Arenas *et al.* are reported in a separate three-year study of the Añamaza River, also located in the Iberian Range in north-east Spain (Auqué *et al.* 2014). Thirdly, Hájek *et al.* (2002) provided data from a contrasting ecological context, tufa-forming fens in the W. Carpathians along the border of the Czech Republic and Slovakia; their study is detailed and highly relevant in the context of paludal tufa-forming springs in Ireland.

Several other localised studies are also used for comparative purposes and data relating to individual vegetation types are compared with my fuzzy cluster plant communities; such data are often lacking in detail and pertain to few chemical variables, but they give useful insights nonetheless. Finally, the water chemistry ranges for individual species are considered.

The implications of certain aspects of the water analysis related to anthropogenic factors are discussed further in Chapter 6 Management.

5.1 Methods

5.1.1 Sample collection and analysis

Water samples were collected islandwide in September 2012 and September 2013. Samples were collected from within relevés where possible and, where appropriate, as close to the point of emergence as possible. However, many relevés and seepages consisted of damp ground with no accumulating or flowing water and often the supply of water was so limited that there were few options of where to collect the sample. In such cases, a location close to the relevé, irrigated by the same source, was chosen.

Samples were collected in unused HDPE plastic bottles. Initially, 568ml bottles were used but later 200ml bottles were found to be more suitable; they contained sufficient water for all analyses and were faster to fill, thus allowing less time for interactions with the atmosphere. At each sample location, two bottles were filled to the brim (thus excluding any air spaces) and capped. At the end of each day in the field, one bottle from each pair was filtered using Gelman 0.45μm sterilised filters. The filtrate was used to fill one 50ml HDPE bottle for cation analysis (acidified with concentrated HNO_3 to pH <2) and one 50ml HDPE bottle for anion analysis. 5ml of filtrate were pipetted into each of three test-tubes for measuring phosphate concentration. The test tubes were sealed with parafilm. All samples were kept cool and returned to the laboratory within three days.

Upon return to the laboratory, the pH of the unfiltered water sample was measured using a Jenway 4330 pH Meter. Alkalinity was measured by titrating 50ml unfiltered water with 0.01mol/l sulphuric acid (dispensed by a 715 Dosimat titrator) to pH4.5. Anion analysis (for nitrate, sulphate and chloride) was carried out using a Dionex ICS-1500 Ion Chromatography System with AS40 Automated Sampler. Cation samples were prepared for analysis by the addition of 1ml 1% CsCl in 10% HNO_3 to each 10ml sample; they were analysed by atomic emission spectroscopy using a Varian Liberty AX Sequential ICP-AES spectrometer. All samples were analysed for calcium, magnesium, potassium and sodium; iron was measured in some samples, Section 5.2.1).

A preliminary investigation of water chemistry was carried out in March 2012. Water samples were collected from fifteen separate locations: six at Glenasmole, Co. Dublin, five at Hartwell, Co. Kildare and four at Louisa Bridge, Co. Kildare. Phosphorus levels were measured both as total phosphorus (TP) and soluble reactive phosphorus (SRP), following the methods of Murphy and Riley (1962) as adapted by Eisenreich *et al.* (1975). Absorbance at 882nm was measured using a

Hach DR5000 spectrophotometer. In all cases, levels were barely detectable (1µg/l to 10µg/l PO_4-P). At these levels, the SRP analysis method detected slightly higher levels of phosphorus than the TP method: the mean concentration for fifteen samples using SRP analysis was 6µg/l PO_4-P, compared to 3µg/l PO_4-P using TP analysis. It was therefore concluded that all phosphates were present as SRP and further TP analysis was not carried out.

5.1.2 Data Analysis

Multi-response Permutation Procedures (MRPP)

The non-parametric method Multi-response Permutation Procedure (MRPP) was used to test for differences in water composition between plant communities (Fuzzy Cluster groups). 108 water samples belonging to my eight Fuzzy Cluster groups, were tested for 10 chemical parameters (pH, alkalinity, calcium, magnesium, potassium, sodium, chloride, nitrate, phosphate and sulphate) using PC-ORD Version 5.33. MRPP produces a statistic *A* that describes within-group homogeneity compared to the random expectation. $A = 1$ when all samples within groups are identical, $A = 0$ when heterogeneity within groups equals expectation by chance and $A < 0$ when within group heterogeneity is greater than that expected by chance (McCune & Grace 2002).

A variant of this method, Blocked MRPP (McCune & Grace 2002), was used to test for differences between two sample collection periods. Data for all chemical parameters (pH, alkalinity, calcium, magnesium, potassium, sodium, chloride, nitrate, phosphate and sulphate) were tested using Blocked MRPP in PC ORD, with sample pairs as blocks and year of sampling as groups, and the statistic *A*, as above, was calculated.

Correlations with NMS Ordination

Spearman rank correlations were calculated for each of the chemical parameters with the axes of the NMS (Non-metric Multidimensional Scaling) ordination of Chapter 3.

5.1.3 Quality Control

Blank samples of deionised water were analysed for anions and cations on three occasions during each field sampling period for quality control purposes. In all cases, ions were below detection.

Ion balance calculations were made for each water sample. More than half of the samples (52%) balanced to within 2% of unity. 86% of samples balanced to within 5% of unity. In 8% of samples,

cations exceeded anions by more than 5% and in 6% of samples anions were in excess by more than 5%.

Nine separate locations (three each at Glenasmole, Hartwell and Louisa Bridge) from which water samples were collected in September 2012 were sampled again in September 2013 to allow a comparison to be made between the two sample collection periods. Blocked MRPP found no significant difference between the two years (A=0.0979, p>0.05). The data from 2012 were used in the final data set because the ion balances were slightly closer to unity than those collected in 2013.

5.2 Results

5.2.1 Chemical composition of Irish petrifying spring water

115 water samples were collected from 91 separate springs (Fig. 5.1). A summary of the results is shown in Table 5.1 and Fig. 5.2 (below). The pH of Irish petrifying springs ranges from 7.00 to 8.47 with a median value of 7.97 and a geometric mean of 7.88 (n=114). Almost half of the samples (49%) have pH values in the range 7.8 – 8.2 (Fig. 5.2a). These levels are comparable to those of tufa-forming habitats studied elsewhere; they are slightly high compared to values presented in an overview of 122 petrifying spring studies of Europe and N. America (Pentecost 2005) and of tufa-forming springs in fens in the W. Carpathians (Hájek *et al.* 2002), and slightly low compared to values measured in tufa-forming waterfalls with bryophytes in R. Piedra (*Arenas et al. 2014*). pH values of tufa-depositing waters reported in other localised studies are broadly within the range of Irish data (Table 5.2 below). At the lower end of the range are median values of 6.97 reported from artesian springs near Lake Eyre, S. Australia, 7.14 for thermal springs at Matlock Bath, central England and 7.5 for springheads near Malham Tarn, N. England (Keppel *et al.* 2011, Pentecost 1981, 1999). Tufa-depositing springs in the Savoie Alps, France, are close to the median for Irish springs with pH 7.86 (Pentecost & Zhaohui 2002), while the lakes of Plitvice National Park, Croatia are towards the upper limit of the Irish range at pH 8.36 (median value, n=24, Emeis *et al.* 1987).

Alkalinity levels in Irish samples range from 109.1 to 644.2 mg/l HCO_3^-, with a median value of 292.8 mg/l (Table 5.1, Fig. 5.2b). River Piedra tufa cascade alkalinity levels lie within the central part of this range (200.1 – 350.2 mg/l, median 277.2 mg/l). Samples from the Plitvice Lakes are

also close to the middle with a median of 261 mg/l (Emeis *et al.* 1987). Springheads near Malham Tarn are at the lower end of the Irish range (median value 165mg/l). Only the study of springheads near Lake Eyre recorded a higher median value (338mg/l) than that of the Irish samples (Table 5.2).

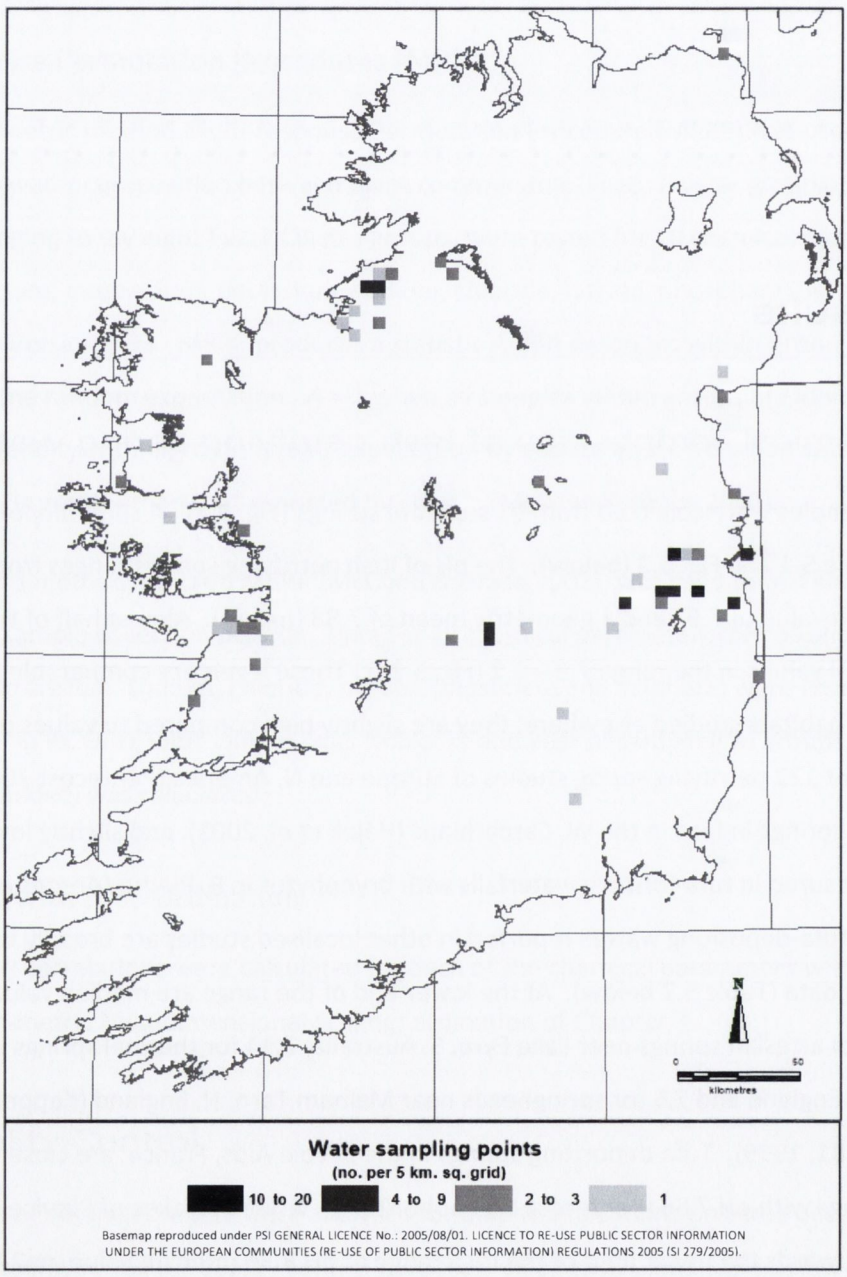


Fig. 5.1: Locations at which water samples were collected (n=115).

Table 5.1: Water analysis from samples collected during the present study from Irish petrifying springs compared with relevant studies outside Ireland.

			Irish Petrifying Springs n = 111 - 115[a]	**A review of tufa-forming springs of Europe & N. America** Pentecost 2005 n = 40 - 122[b]	**Tufa cascades with bryophytes River Piedra, Spain** Arenas *et al.* 2014 n = 80[c]	**Tufa-forming brown moss fens W. Carpathians** Hájek *et al.* 2002 n = 26
pH		mean	7.88[d]	7.39[d]	-	7.6
		median	7.97	7.55	8.13	-
		range	7.00 – 8.47	6.9 – 8.15	6.91 - 8.81	-
HCO_3^-	mg/l	mean	293.7 (SD 93.0)	-	-	-
	mg/l	median	292.8	-	277.2	-
	mg/l	range	109.1 - 644.2	-	200.1 - 350.2	-
Ca^{2+}	mg/l	mean	87.80 (SD 29.10)	123.04	-	231 (SD 90)
	mg/l	median	84.50	93.38	88.0	-
	mg/l	range	19.08 – 181.22	34.47 – 609.2	64.3 - 107.8	-
Mg^{2+}	mg/l	mean	10.11 (SD 7.91)	16.77	-	11.4 (SD 4.8)
	mg/l	median	8.15	10.69	26.8	-
	mg/l	range	0.22 – 30.56	0.024 – 66.6	13.2 - 29.0	-
K^+	mg/l	mean	1.75 (SD 2.30)	3.91	-	3.4 (SD 2.2)
	mg/l	median	0.91	-	2.1	-
	mg/l	range	0.14 – 10.40	0.078 – 74.29	2.0 - 6.3	-
Na^+	mg/l	mean	15.52 (SD 15.27)	11.72	-	10.1 (SD 7.2)
	mg/l	median	8.97	-	6.9	-
	mg/l	range	5.10 – 82.31	0.276 – 45.975	3.1 - 10.3	-
Cl^-	mg/l	mean	24.16 (SD 24.77)	-	-	6.1 (SD 9.5)
	mg/l	median	14.61	-	16.4	-
	mg/l	range	6.98 - 131.89	-	10.0 - 26.0	-
NO_3^-	mg/l	mean	5.09 (SD 8.78)	4.0	-	0.69 (SD 1.1)
	mg/l	median	1.56	-	-	-
	mg/l	range	<0.07 – 44.05	0.1 – 16.1	-	-
PO_4^{3-}	µg/l	mean	16 (SD 19)	275	-	70 (40)
	µg/l	median	13	-	-	-
	µg/l	range	2 - 140	2 - 437	-	-
SO_4^{2-}	mg/l	mean	14.27 (SD 16.09)	-	-	45.3 (SD 33.2)
	mg/l	median	8.28	-	107.0	-
	mg/l	range	<0.06 - 96.25	-	29.8 - 143.0	-

[a] Up to four outliers removed from total sample of 115 for individual parameters; see text for details

[b] n=122 for pH; n=107 for Ca^{2+}; n=75 for Mg^{2+}; n=45 for K^+; n=73 for Na^+; n=40 for NO_3^-

[c] Samples are from four locations (Facies C), replicated up to 24 times over a 13 yr period

[d] Geometric mean

- data not provided

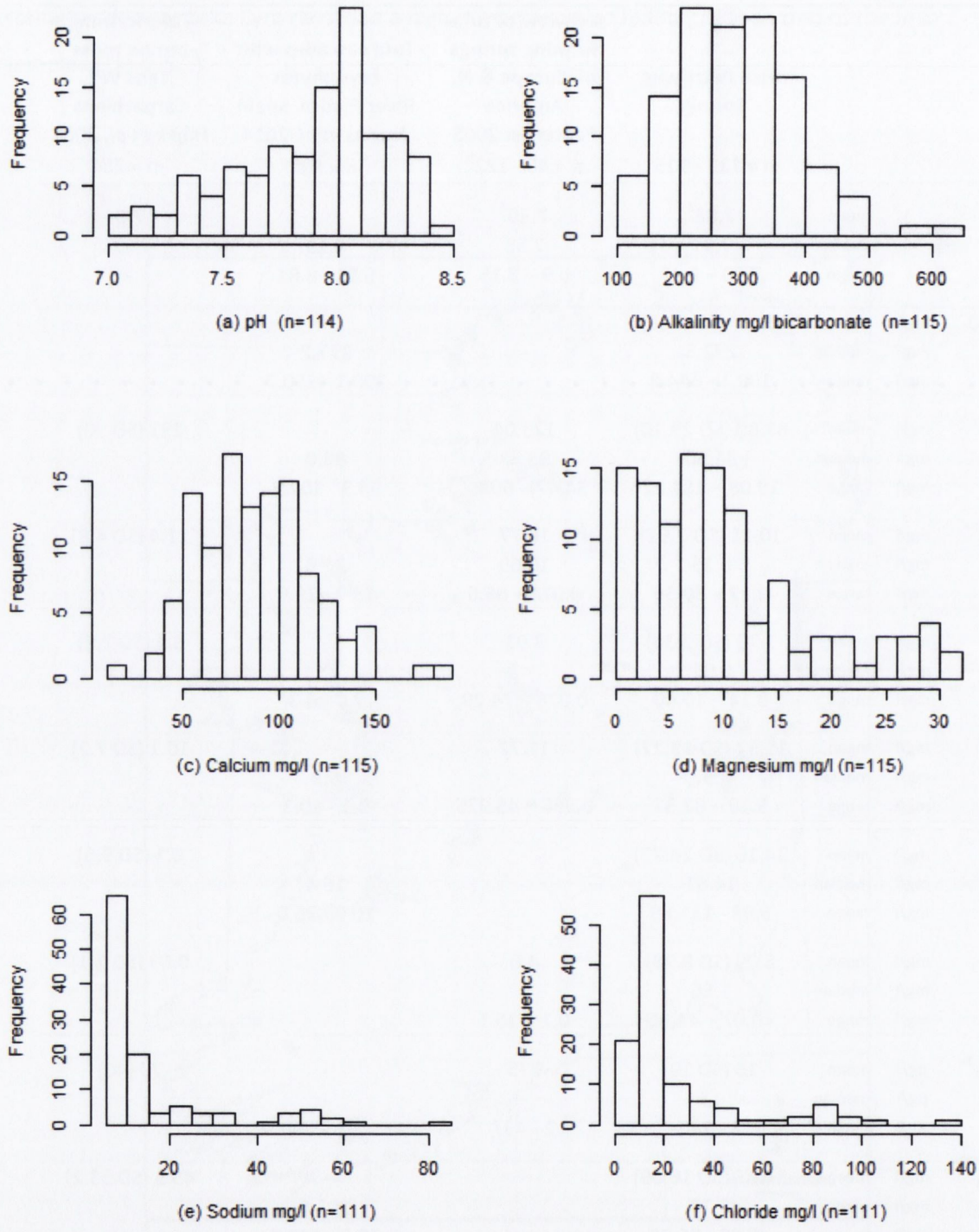


Fig 5.2: Water chemistry parameters for Irish petrifying springs (outliers excluded, as per Table 5.3)

(*Continued below)*

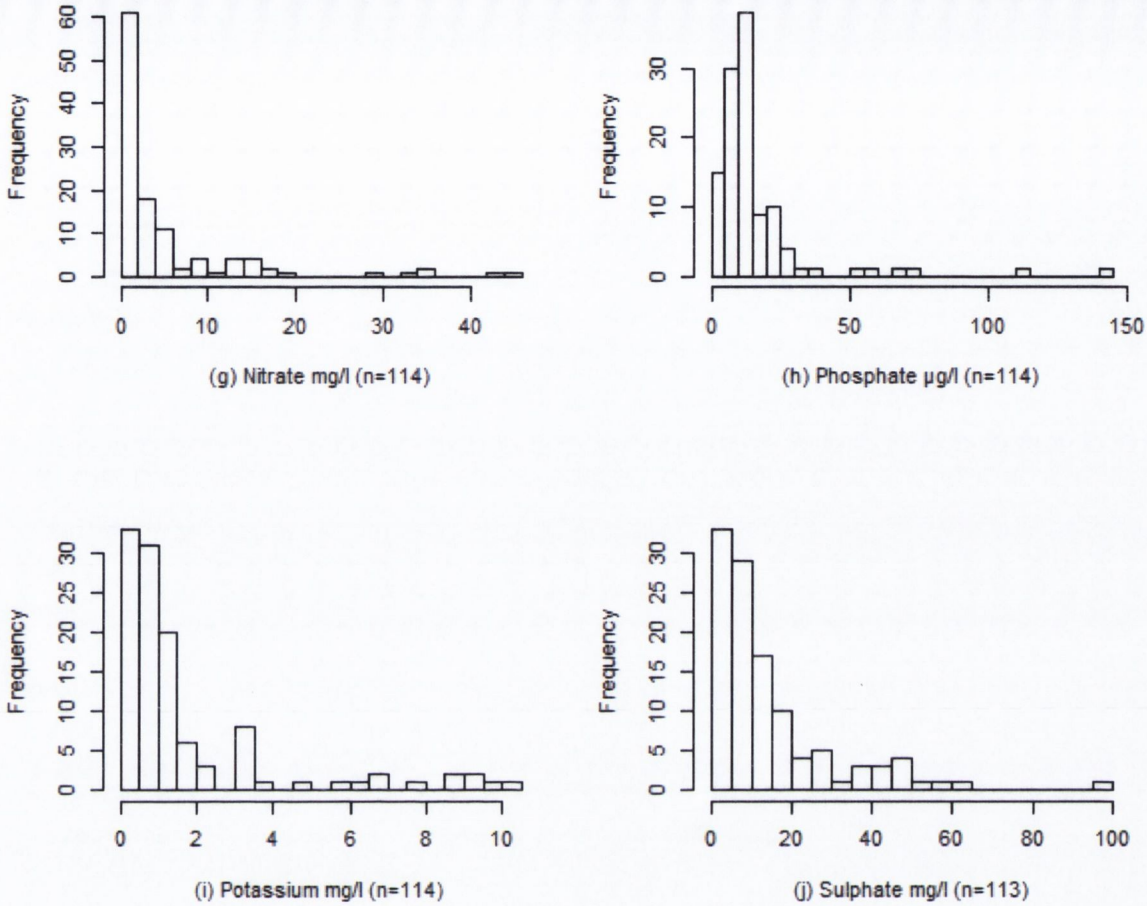


Fig 5.2 (*contd*): Water chemistry parameters for Irish petrifying springs (outliers excluded, as per Table 5.3 below)

The cations calcium, magnesium and potassium are present at broadly comparable, although slightly lower, levels in Irish petrifying springs compared to tufa forming springs elsewhere. Levels of calcium in Irish petrifying springs range from 19.08 to 181.22 mg/l with a median value of 84.50 mg/l. Calcium levels in the R. Piedra have a similar median value, 88.0 mg/l; their range is narrower and centrally located within the Irish range, at 64.3 to 107.8 mg/l. The median value in Pentecost's review of European and N. American tufa-forming springs is close to that of Irish samples at 93.38 mg/l, but the range extends up to 609.2 mg/l. Tufa-forming fens of the W. Carpathians have much higher calcium levels; the mean value is 231mg/l, well in excess of the maximum value recorded in the present Irish study. Median values for calcium levels in the Matlock Bath, Savoie Alps and Lake Eyre studies are slightly higher than the Irish levels (97.0 – 104.8 mg/l), but springs near Malham Tarn have lower levels (54.9 mg/l).

The range for magnesium levels in Irish samples is 0.22 – 30.56 mg/l, with a median value of 8.15 mg/l. The median value for European and N. American springs is similar, 10.69 mg/l, although values can range up to 66.6 mg/l. The range for R. Piedra samples lies in the upper half of the Irish range, with a higher median value of 26.8 mg/l. The spring water studied near Lake Eyre is even richer in magnesium, with a median value of 38.3 mg/l. However, for magnesium to influence the mineralogy of the precipitated tufa, it needs to approach 240 mg/l (Pentecost 2005); none of these studies reported values close to this.

Potassium levels in Irish petrifying springs, 0.14 – 10.40 mg/l with a median value of 0.91 mg/l, are comparable to other studies, although values reported from European and N. American tufa-forming spring waters can be as high as 74.29 mg/l. The R. Piedra range falls within the Irish range and Malham Tarn and Matlock Bath samples have the same median levels as the Irish samples. As with magnesium, potassium levels in the Lake Eyre study are much higher, with a median value of 48.4 mg/l.

Table 5.2: Irish petrifying spring water composition compared with local studies of tufa-forming waters. Data are median values.

		Irish Petrifying Springs	Malham Tarn Pentecost 1981	Matlock Bath Pentecost 1999	Savoie Alps Pentecost & Zhaohui 2002	Lake Eyre Keppel *et al.* 2011
n[a]		111 to 115	3 to 5	4 to 5	4 to 8	8
pH		7.97	7.5	7.14	7.86	6.97
HCO_3^-	mg/l	293	165	262	245	338
Ca^{2+}	mg/l	84.5	54.9	97.0	101.4	104.8
Mg^{2+}	mg/l	8.15	0.8	34.0	12.9	38.3
K^+	mg/l	0.91	0.9	0.8	<0.1	48.4
Na^+	mg/l	8.97	3.8	25.4	6.0	1440
Cl^-	mg/l	14.61	na	40.8	5.3	1857
NO_3^-	mg/l	1.56	<0.1	13.2	-	-
PO_4^{3-}	µg/l	13	4	1102	-	-
SO_4^{2-}	mg/l	8.28	14.2	132.1	60.5	330

[a] sample numbers vary for different parameters

- data not provided

Sodium and chloride median levels (8.97 mg/l Na^+ and 14.61 mg/l Cl^-) are close to those of the River Piedra, but the range for Irish samples (5.1 – 82.3 mg/l Na^+ and 7.0 – 131.9 mg/l Cl^-) is much wider, due in part to the coastal influence at several sites. Similarly, the mean values for Irish samples are higher than the inland W. Carpathian samples. However, the thermal springs at

Matlock Bath and near Lake Eyre have much higher concentrations of these ions; this is discussed further below in the section on outlying values.

Nitrate levels in Irish samples vary from below detection (<0.07 mg/l) to 44.05 mg/l. The mean value, 5.09 mg/l, is close to that for European and N. American springs calculated by Pentecost (4.0 mg/l, n=40) but the upper limit of the range for Irish samples (n=114) is higher; 8% of my samples exceed the upper limit of the range reported by Pentecost. 24% of my samples were at levels below detection, *i.e.* below 0.07 mg/l; at the level of accuracy available, this lower limit cannot be distinguished from the lowest level reported by Pentecost of 0.1 mg/l. Nitrate levels in the W. Carpathians are very low by comparison, with a mean of 0.69 ± 0.22 mg/l.

Phosphate concentrations in Irish samples are low compared to other studies. At most springs, they were barely detectable (<30 µg/l in 92% of samples). The mean value, 16 µg/l, is extremely low compared to that of European and N. American tufa-forming springs in general (275 µg/l) and also to that of springs in the W. Carpathians (70 µg/l).

Sulphate levels are very variable (<0.06 – 96.25 mg/l) but, on the whole, they are low in Irish samples. The median value, 8.28 mg/l, is the lowest of all studies presented in Tables 5.1 and 5.2. The median value for R. Piedra (107.0 mg/l) exceeds the upper limit of the range of Irish samples. The mean value of Irish samples (14.27mg/l) is much lower than that of the W. Carpathian samples (45.3mg/l). The Savoie Alps and Matlock Bath studies report higher median values than that of Irish springs, and the Lake Eyre study recorded the highest median concentration, at 330mg/l.

Iron concentrations are not usually reported in petrifying spring water analysis (*e.g.* Pentecost 1981, 1999, Pentecost & Zhaohui 2002, Keppel *et al.* 2011, Arenas *et al.* 2014). In the review of European and N. American springs there are only 5 samples; these range from 0.01 to 0.17 mg/l with a mean value of 0.07 mg/l. Iron concentrations were measured in 68 samples in the early stages of this study. Most of these (90%) contained <0.050 mg/l; the maximum value was 0.180 mg/l. Subsequently, two springs were noted in the field to be exceptionally rich in iron and so samples were collected and tested. One was located at Ballyman Glen (WS066) and contained 7.14 mg/l iron (Photo 5.7); the other, at Glenasmole, contained 1.85 mg/l iron. In spite of the conspicuous discolouration on the ground, these spring waters contained low iron concentrations compared to those reported from tufa-forming springs in the W. Carpathians, where the mean concentration is 28.6 mg/l (SD 18.7).

Outlying values

Up to four outlying values per chemical parameter were removed from the data presented in Tables 5.1, 5.2 and Fig. 5.2 to avoid skewing the means and ranges unduly; 14 values were removed in total (Table 5.3).

One outlying pH value of 11.38 was removed (WS032). This was recorded at an unusual tufaceous cascade on the coast at Spanish Point, Co. Clare (Photos 5.1 and 5.2). The surface of the tufa showed a distinctive, honeycomb-like pattern not found elsewhere during the survey. This cascade was almost devoid of vegetation; vascular plants were confined to the uppermost edge (QL139 with six species, mostly graminoids, and overall plant cover of 9%) and filamentous green algae colonised the lower part. It fitted poorly in the fuzzy cluster arrangement (highest membership coefficient 25%, Group 7).

Table 5.3: Outlying values excluded from Tables 5.1, 5.2 and Fig. 5.2.

Ref.	Relevé	Location	Parameter	Value
WS032	QL139	Coast at Spanish Point, Co. Clare	pH	11.38
WS048	QL155	coast near Skerries, Co. Dublin	K^+	22.97 mg/l
WS013	QL031	Louisa Bridge (pool on upper terrace)	Na^+	210.92 mg/l
WS013	QL031	Louisa Bridge (pool on upper terrace)	Cl^-	410.22 mg/l
WS014	-	Louisa Bridge (pool in cliff between terraces)	Na^+	225.38 mg/l
WS014	-	Louisa Bridge (pool in cliff between terraces)	Cl^-	423.13 mg/l
WS015	QL123	Louisa Bridge (pool on lower terrace)	Na^+	209.42 mg/l
WS015	QL123	Louisa Bridge (pool on lower terrace)	Cl^-	413.89 mg/l
WS082	QL036	Ardmore Point coastal spring	Na^+	265.88 mg/l
WS082	QL036	Ardmore Point coastal spring	Cl^-	258.54 mg/l
WS067	QL120	Ballyman Glen Fen	NO_3^-	64.70 mg/l
WS139	QL159	R. Liffey valley, Woodlands	PO_4^{3-}	991 µg/l
WS137	QL156	R. Liffey valley, Fonthill	SO_4^{2-}	146.88 mg/l
WS138	QL157	R. Liffey valley, Fonthill	SO_4^{2-}	142.22 mg/l

A value of 22.97 mg/l of potassium, more than twice the next highest value, was excluded (WS048). It was recorded at a small, atypical, tufa cascade on the coast near Skerries, Co. Dublin, which was forming on a retaining wall below a pipe outfall (Photos 5.3 and 5.4). Water from the adjacent hillside, along which a road and train line run, is channelled into numerous drainage pipes which discharge onto the beach along this section of coast; small tufa deposits colonised by

bryophytes and algae have formed below several pipes. The tufa formation at which this water sample was collected was dominated by *Didymodon tophaceus*, with small amounts of *Cochlearia officinalis* and *Agrostis stolonifera* (QL155). Filamentous green algae (*Cladophora glomerata* and *Rhizoclonium hieroglyphicum*) occupied the margins of the tufa, where the trickling water was most plentiful. This was one of the locations at which tufa deposition rates were measured (TB15, Chapter 7).

Four samples contained extremely high levels of both sodium and chloride and these values were excluded (WS013 – WS015, WS082, Table 5.3). Three of these samples were collected at an inland site, Louisa Bridge, Leixlip, Co. Kildare (Photos 5.5 and 5.6), and the fourth was from Ardmore Point on the Co. Wicklow coast. The site at Louisa Bridge consists of a complex of springs and seepages fed by two separate water sources: a deeper, older and warmer artesian groundwater system with high concentrations of sodium and chloride, and a more recent, shallow, alkaline groundwater system (Kuczynska and Bartley 2008). The water from the two sources mixes as it trickles down the hillside towards the Rye Water River, creating a series of shallow pools and paludal habitats, from which the water samples WS013 – WS015 were collected. The unusual ecological conditions give rise to species-rich, sedge-dominated vegetation with an abundant brown moss underlayer and paludal tufa of intermediate strength. Five relevés recorded at this site had a mean of 29.8 species per $4m^2$; all were assigned to *Carex lepidocarpa* Small Sedge Springs. Louisa Bridge is the only site in the present study at which thermal spring water contributed to the formation of tufa. The Matlock Bath and L. Eyre spring systems (Table 5.2) are also thermal artesian springs. The complex hydrogeological conditions in all three systems give rise to very high levels of sodium and chloride. The mean concentrations recorded at Louisa Bridge in water samples WS013 – WS015 were 215.24 mg/l Na^+ and 415.75 mg/l Cl^-; these values are intermediate between those of Matlock Bath (25.4 mg/l Na^+ and 40.8 mg/l Cl^-) and the exceptionally high concentrations in springs near L. Eyre (1440 mg/l Na^+ , 1857 mg/l Cl^-).

The water sample from Ardmore point (WS082) was collected below a small spring, with a very low flow rate, issuing onto coastal spray zone rocks. Water was collected where it ponded just below the springhead and it had probably been subjected to evaporation, and therefore concentration of solutes, prior to collection. Other coastal samples contained 20.90 – 82.31 mg/l sodium and 31.89 – 131.89 mg/l chloride.

One value for nitrate concentration was excluded. It was recorded at Ballyman Glen, Co. Wicklow (WS067, Photo 5.8) and measured 64.70 mg/l. The source of nitrate detected in the water sample is unknown; a possible source is an adjacent domestic refuse landfill site, now closed.

One sample contained an exceptionally high concentration of phosphate, an order of magnitude greater than the next highest value. This sample, WS139, with 991 µg/l phosphate was collected on the north side of the River Liffey valley near Palmerstown, Co. Dublin, from a tufa cascade at the overflow of a lake situated within a golf course (Photos 5.9 to 5.10). This value exceeds the maximum reported by Pentecost for European and N. American tufa-forming springs (mean 275 µg/l, max. 437 µg/l) but it is slightly lower than the median value measured at Matlock Bath (1,102 µg/l).

Two values for sulphate were excluded: WS137 with 146.88 mg/l and WS138 containing 142.22 mg/l sulphate. Both were collected in a small stream with tufaceous dams, a tributary on the south side of the River Liffey, near Palmerstown. This stream was visibly polluted; a pipe above the stream carried surface drainage water from the lands above (Photos 5.11 and 5.12). Tufa deposits were uncharacteristically dark in colour and showed signs of erosion.

Magnesium to Calcium Ratio

Most tufa-depositing waters have a Mg:Ca ratio of less than 15% (Pentecost 2005); high ratios are often due to the presence of dolomite $CaMg(CO_3)_2$ in the catchment. Magnesium is also a major ion in seawater (1.286 g/kg, Duke & Williams 2008) and, on the whole, Irish coastal spray zone spring samples had high Mg:Ca concentrations. The highest ratio was 61% magnesium at Old Head on the coast of Co. Mayo (Table 5.4). Other high values for coastal samples were from Marconi's Cottage, Co. Antrim; Ardmore Point, Co. Wicklow; Balscadden and Kilrock Quarry, Howth, Co. Dublin. Inland sites with high Mg:Ca ratios were Moneyduff Wood, Co. Leitrim and Pollardstown Fen, Kingsbog and Louisa Bridge, Co. Kildare. The bedrock formations beneath these sites are complex and catchments were not investigated during the present study. However, it is worth noting that Pollardstown Fen is underlain, in part, by the Rickardstown Formation, which contains fine-grained dolomite, at least 40m thick in places (McConnell 1994), which may contribute to the magnesium concentrations of water samples.

Most samples had much lower Mg:Ca ratios; in 60% of samples the proportion of magnesium was less than 10%. All samples from the Burren were very low in magnesium with ratios not exceeding 3%. Samples from the Slieve Bloom Mountains were also notably low (3% to 5%, with one exception of 11%, n=10).

Table 5.4: Water samples with high magnesium to calcium ratios

Sample	Site	County	Coastal/Inland	Mg:Ca
WS031	Old Head	Mayo	<1km coast	61%
WS103-105	Moneyduff Wood	Leitrim	Inland	37% to 42%
WS131,	Marconi's Cottage	Antrim	Coastal spray zone	39%
WS082	Ardmore Pt	Wicklow	Coastal spray zone	39%
WS113-115	Pollardstown Fen	Kildare	Inland	22% to 37%
WS133	Balscadden Beach	Dublin	Coastal spray zone	34%
WS134, 135	Kilrock Quarry	Dublin	<1km coast	30% to 34%
WS112	Kingsbog	Kildare	Inland	30%
WS013 – 15	Louisa Bridge	Kildare	Inland	28% to 30%

Relationship of pH and alkalinity

Within the range of the chemical composition of petrifying spring water, alkalinity decreases as pH increases (Fig. 5.3). The relationship is very highly statistically significant (r^2=0.3285, p=2.67 x 10^{-11}).

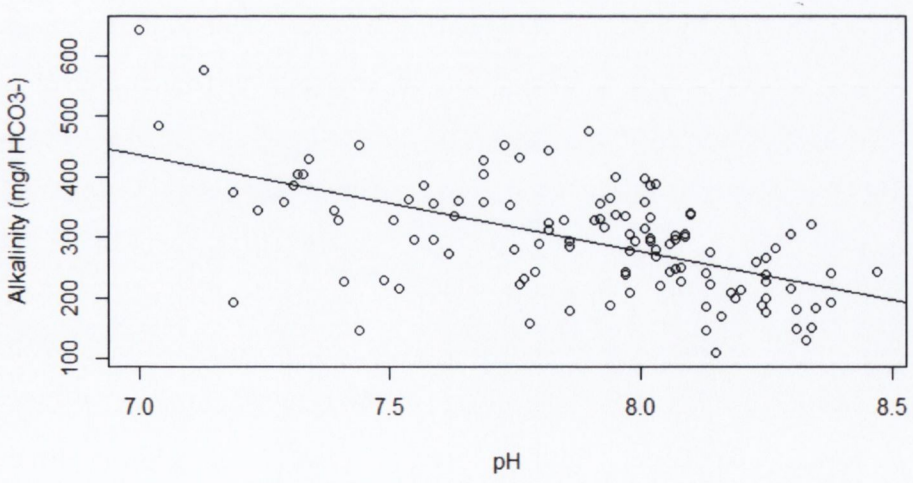


Fig. 5.3: Relationship between pH and alkalinity for Irish petrifying spring water samples (n=114)

This pattern is counterintuitive; over a broader pH spectrum, there is a strong positive correlation between these factors. Within the petrifying spring range, however, the degassing of spring

water on contact with the atmosphere causes pH to increase as concentrations of dissolved CO_2 decrease. In tandem with this change, tufa is precipitated, lowering the calcium and bicarbonate levels in the water. This pattern is characteristic of tufa-depositing waters (*e.g.* Auqué *et al.* 2014, Arenas *et al.* 2014, Vázquez-Urbez *et al.* 2010).

5.2.2 Plant Communities and Water Composition

108 water samples were collected from relevés (n=186) assigned to the plant communities in Chapter 3. It was not possible to revisit all sites within the water sampling periods (September 2012 and September 2013). Sites of high conservation value, those which were considered to be good examples of their type and larger sites or those with several springs were prioritised. Thus, four distant locations, each with a single relevé, are not represented in the water analysis survey. Some of the smaller springs in the Slieve Blooms and the Burren were not revisited, but these localities are well represented by water samples from the main spring areas. It was not always possible to collect individual water samples from each relevé as many had no surface water; in such cases, nearby relevés irrigated by the same spring are represented by the same water sample. Two sites visited in September 2013, Thomastown Quarry and Clonaslee Esker (from which 4 relevés were recorded in total) are not represented in the water chemistry analysis as there was no water present on site following the dry summer that year. In total therefore, water analysis was carried out for 163 relevés out of the total number of 186 described in Chapter 3.

The chemical composition of spring water varies among plant communities (Fig. 5.4 below). MRPP indicates that there are statistically significant differences in the composition of the spring water of different plant communities of petrifying springs (A=0.1749, $p<0.0001$). Pairwise comparisons (Table 5.5) show that the chemical composition of spring water in Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs is highly significantly different to that of all other groups except Group 7 *Palustriella falcata-Carex panicea* Springs ($p<0.01$ with Dunn-Šidák correction for multiple comparisons). The water composition of the strongly tufa-forming Group 2 *Palustriella commutata-Geranium robertianum* Springheads is significantly different to that of small-sedge paludal tufa-forming communities (Groups 5 – 7, $p<0.01$). Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes contain water of significantly different composition to that of Group 7 *Palustriella falcata-Carex panicea* Springs ($p<0.01$).

Table 5.5: MRPP statistically significant differences of spring water composition between plant communities. Dunn-Šidák correction for multiple comparisons applied to p-values.

Group	1	2	3	4	5	6	7	8
1	-	ns	ns	ns	*	ns	*	**
2		-	*	ns	***	***	***	***
3			-	ns	**	ns	***	***
4				-	ns	ns	*	***
5					-	ns	ns	**
6						-	ns	**
7							-	ns

Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs have a higher pH than other groups and, on the whole, they have lower concentrations and smaller ranges for the ions tested compared to other groups (Fig. 5.4 below). Alkalinity and calcium levels are especially low. Likewise, Group 7 *Palustriella falcata-Carex panicea* Springs have low levels of the ions tested compared to other groups (apart from Group 8); alkalinity and calcium are almost as low as in Group 8. Magnesium is very low in both Groups 7 and 8.

The lowest pH values are in Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs; these groups have relatively high alkalinity levels. Groups 1 to 4, the most strongly tufa-forming communities, have high pH values along with moderate to high alkalinity and calcium levels compared to other groups. They also contain somewhat higher levels of the nutrients nitrate, phosphate and potassium.

The relationship between pH and alkalinity amongst different plant communities is illustrated in Fig. 5.5 below. Fuzzy cluster plant communities are combined into three clusters on the basis of their water composition. Groups 1 – 4, the most strongly tufaceous communities, have the highest alkalinity levels relative to pH. The relationship between alkalinity and pH in this cluster is very highly significant (r^2=0.580, p=2.44 x 10^{-12}). Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs, which have moderate tufa-formation and lower pH values, also show a strong pattern of declining alkalinity with increasing pH (r^2=0.363, p=0.000543). Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs and Group 7 *Palustriella falcata-Carex panicea* Springs are, on the whole, weakly tufa forming; they have low levels of alkalinity across their pH range and there is no significant relationship between these parameters (r^2=0.041, p=0.409).

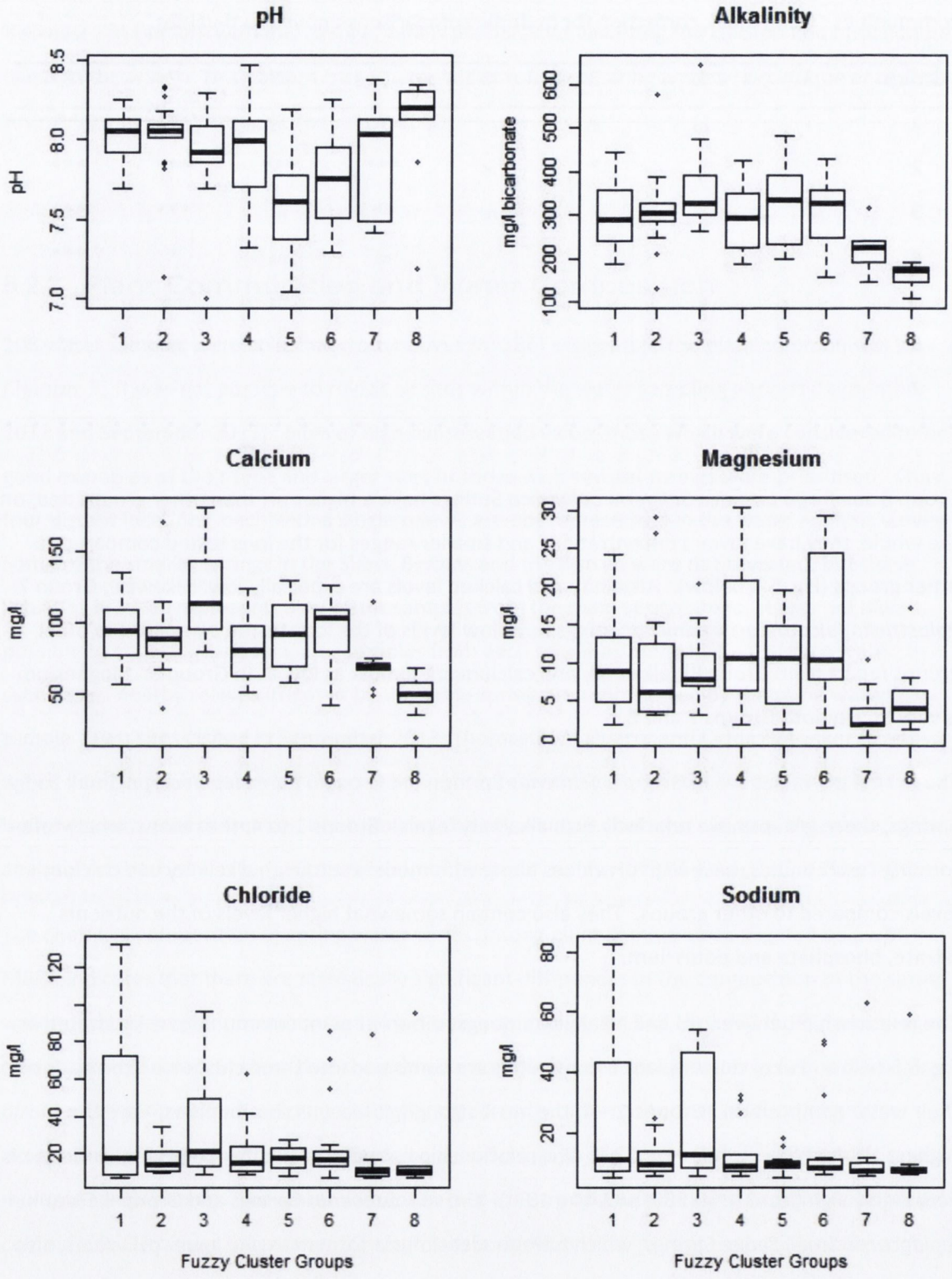


Fig. 5.4: Spring water composition in plant communities. See key below for Fuzzy Cluster Groups and see Table 5.6 for data (*Continued below*).

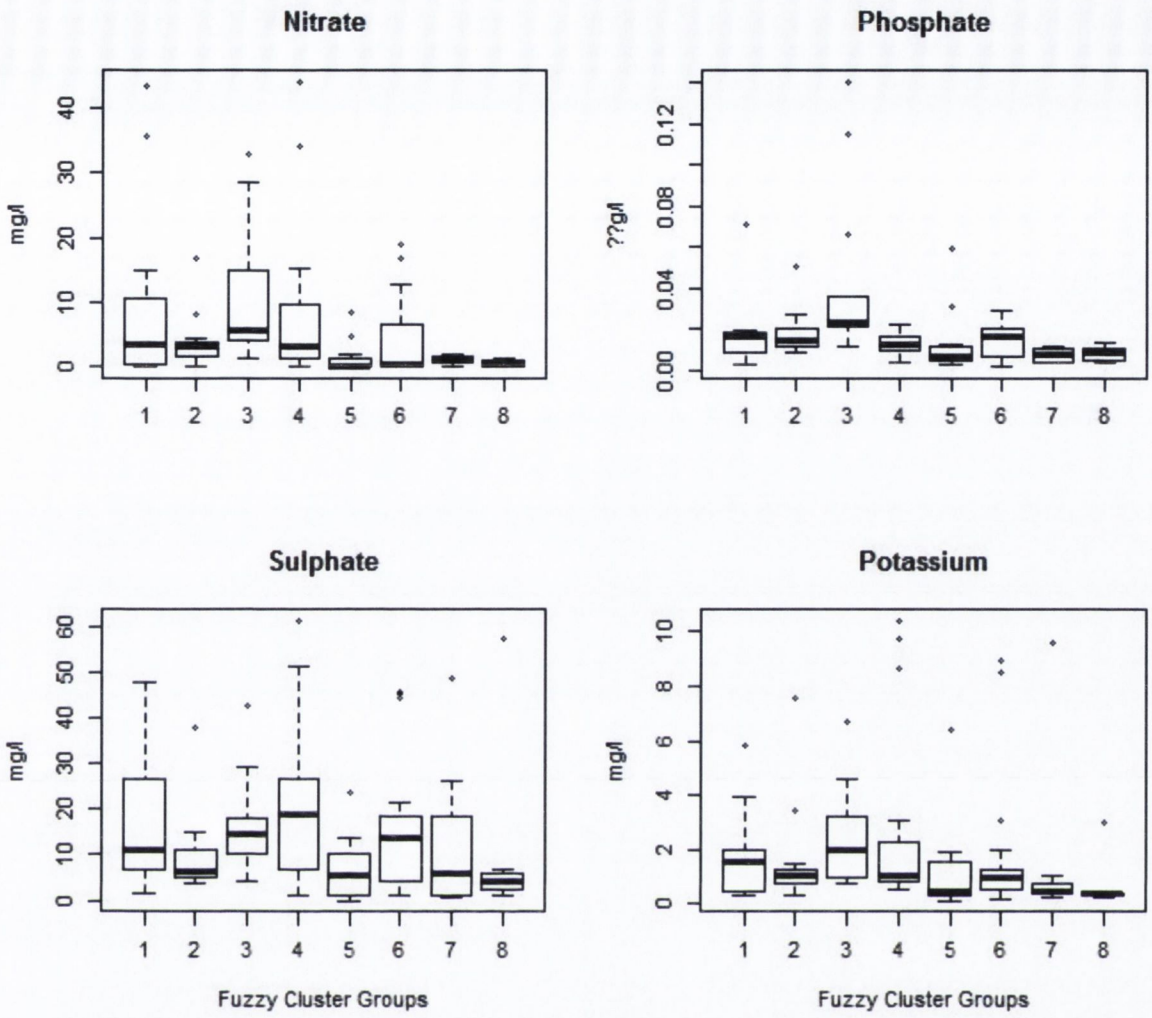


Fig. 5.4 (*contd*): Spring water composition in plant communities. See key below for Fuzzy Cluster Groups and see Table 5.6 for data.

Key to Fuzzy Cluster Groups (see Chapter 3 for details)

Group 1: *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades

Group 2: *Palustriella commutata-Geranium robertianum* Springheads

Group 3: *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes

Group 4: *Palustriella commutata-Agrostis stolonifera* Springheads

Group 5: *Schoenus* Springs

Group 6: *Carex lepidocarpa* Small Sedge Springs

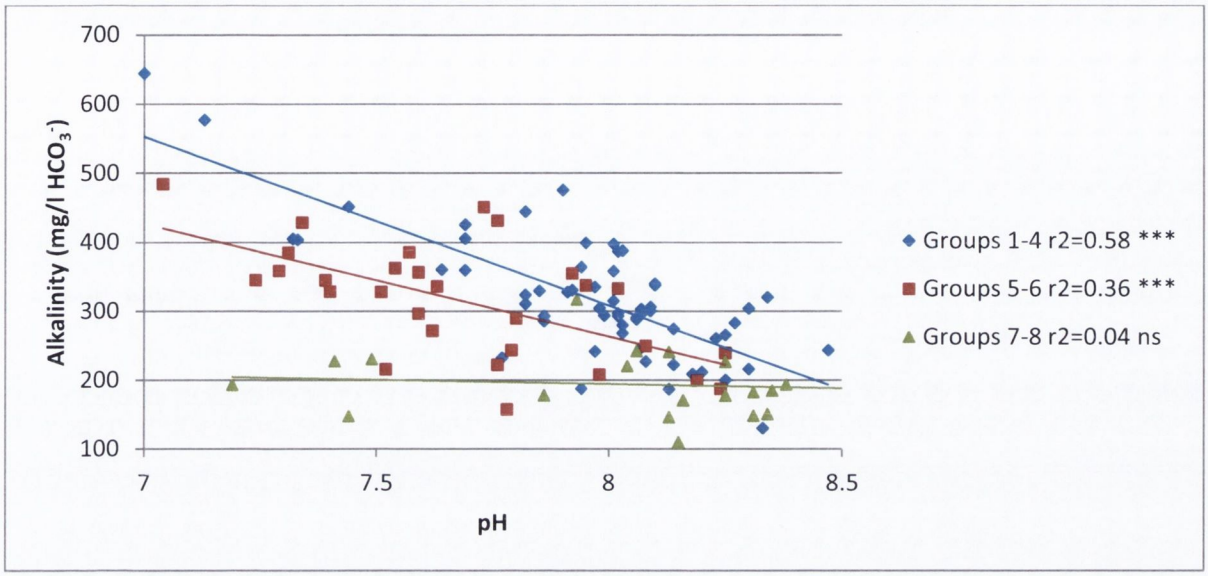
Group 7: *Palustriella falcata-Carex panicea* Springs

Group 8: *Saxifraga aizoides-Seligeria oelandica* Springs

Table 5.6: Water analysis by plant community (Gr. = fuzzy cluster group; see key above). Data are mean, median and range. Values in mg/l, except phosphates in µg/l.

	Gr. 1	Gr. 2	Gr. 3	Gr. 4	Gr. 5	Gr. 6	Gr. 7	Gr. 8
	n=13	n=17	n=14	n=15	n=12	n=17	n=10	n=10
pH	7.96	7.89	7.76	7.79	7.50	7.64	7.81	7.91
	8.06	8.06	7.93	7.99	7.61	7.76	8.05	8.21
	7.69 - 8.25	7.13 - 8.34	7.00 - 8.30	7.32 - 8.47	7.04 - 8.19	7.29 - 8.25	7.41 - 11.38	7.19 - 8.35
HCO_3^-	301	312	363	296	329	305	221	164
	290	303	326	294	334	328	227	174
	186 - 444	129 - 576	265 - 644	187 - 427	199 - 484	157 - 431	147 - 317	109 - 193
Ca^{2+}	92.10	89.72	119.10	82.82	91.72	91.26	70.52	48.29
	94.42	88.64	113.44	80.06	92.21	103.02	69.12	49.89
	56.01 - 135.34	39.25 - 170.23	78.73 - 181.22	50.92 - 124.28	57.34 - 129.36	40.90 - 125.57	48.60 - 114.64	19.08 - 68.18
Mg^{2+}	10.02	9.45	9.20	13.50	10.13	14.42	3.42	5.20
	8.85	6.18	7.76	10.61	10.52	10.39	1.85	4.02
	1.74 - 24.26	3.12 - 29.13	3.13 - 20.46	1.78 - 30.44	1.10 - 19.43	1.42 - 29.28	0.22 - 10.32	1.14 - 17.24
K^+	1.77	1.47	3.81	2.82	1.19	1.89	1.42	0.62
	1.54	1.07	2.11	1.02	0.49	0.97	0.44	0.38
	0.29 - 5.82	0.31 - 7.57	0.74 - 22.97	0.54 - 10.40	0.14 - 6.39	0.16 - 8.92	0.27 - 9.61	0.24 - 3.02
Na^+	25.84	11.30	22.37	30.13	10.30	39.75	13.38	12.65
	11.10	9.62	12.62	9.11	9.57	9.18	7.52	7.40
	5.47 - 82.31	5.91 - 24.78	5.97 - 54.19	5.63 - 265.88	5.10 - 18.21	6.49 - 225.14	5.70 - 62.88	6.33 - 59.00
Cl^-	42.05	16.89	35.26	36.93	17.35	45.46	17.55	18.76
	18.10	14.61	21.44	15.18	17.56	17.29	10.39	10.40
	7.17 - 131.89	9.41 - 34.18	9.09 - 96.46	8.52 - 258.54	7.65 - 27.71	7.13 - 195.95	6.98 - 84.21	7.03 - 94.88
NO_3^-	9.60	3.63	10.83	8.80	1.29	7.68	0.98	0.44
	3.48	3.12	5.47	2.93	<0.07	0.65	1.07	0.16
	<0.07 - 43.5	<0.07 - 16.61	1.19 - 32.99	<0.07 - 44.05	<0.07 - 8.44	<0.07 - 64.70	<0.07 - 1.87	<0.07 - 1.34
PO_4^{3-}	17	18	109	13	13	15	8	8
	16	15	24	13	6	16	8	9
	3 - 71	9 - 51	13 - 991	4 - 20	3 - 59	2 - 29	4 - 12	4 - 14
SO_4^{2-}	18.02	9.52	34.45	19.71	6.71	16.10	11.76	9.11
	11.10	6.48	15.42	18.67	5.53	13.57	5.68	4.19
	1.53 - 48.01	3.49 - 38.03	4.09 - 146.88	1.04 - 61.40	<0.06 - 23.82	1.02 - 45.71	0.85 - 48.73	1.20 - 57.20

Fig. 5.5: Relationship between pH and Alkalinity in different plant communities.



The difference in the relationships between alkalinity and pH shown by the three clusters is statistically significant. Analysis of variance between the linear model of all samples combined (depicted in Fig. 5.3 above) compared with the model taking account the interaction between pH and the three clusters (shown in Fig. 5.5) shows that there is a very highly significantly difference ($F=37.96$, $df=2$, $p=4.46 \times 10^{-13}$).

In their levels of pH, alkalinity and calcium, as well as hydrologically and floristically, the River Piedra tufa cascades are most similar to Groups 1 to 4 (high pH, moderate alkalinity and calcium, Tables 5.1 and 5.6), while the W. Carpathian tufa-forming fens are closest to Groups 5 and 6 (lower pH, high calcium concentrations).

Water chemistry in other published plant community descriptions

Scant water chemistry data are reported for the published plant community descriptions discussed in Chapter 4. Where data are given, they often span an uninformatively broad range, especially for pH, and few details are given other than the upper and lower limits of the range (Table 5.7). However, individual water sample data are given in the Scottish Highlands (McVean and Ratcliffe 1962) and Isle of Skye (Birks 1973) studies for some spring and mire communities.

The *Cratoneuron commutatum-Saxifraga aizoides* nodum springs in these two studies have lower pH values than my samples. Their median pH values are 7.3 and 7.1 (Scottish Highlands and Isle

of Skye respectively). The Irish communities with the most similar vegetation, Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs and, to a lesser extent, Group 4 *Palustriella commutata-Agrostis stolonifera* Springheads, have median pH values of 8.21 and 7.99 respectively. The levels of calcium are much higher in the Scottish Highlands samples (median 38.87 mg/l) than those from the Isle of Skye (median 8.5mg/l) and their ranges do not overlap. The higher levels in the former study are close to my Group 8 samples, both in median (49.89 mg/l) and range. My Group 4 samples have higher concentrations of calcium (median 80.06 mg/l). Concentrations of magnesium, sodium and potassium were also measured in the Isle of Skye study; the ranges for these ions fall within the Irish Group 8 ranges (there are four Isle of Skye samples compared to 10 Irish samples).

Water analysis was carried out for three sedge-dominated flush and mire communities in the Scottish studies. pH levels decline moving from the springhead communities to the associated flush communities, the *Cariceto-Saxifragetum aizoidis* (McVean and Ratcliffe 1962) and the *Eriophorum latifolium-Carex hostiana* Association (Birks 1973); they are lower still in the mire which typically flanks these flushes, the *Carex panicea-Campylium stellatum* Association (Birks 1973). Both of the flush communities have median pH values of 6.8 (and their pH ranges are very similar to each other), and both have comparable levels of calcium (median values 9.05 mg/l and 8.4 mg/l respectively). Two of my sedge-dominated communities, Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs, have low pH values compared to my other groups, but their median values of 7.61 and 7.76 are considerably higher than those of the Scottish communities. Similarly, the calcium levels in the Scottish communities are very much lower than those of any of my groups; indeed, the ranges of the Scottish and Irish samples do not even overlap (Scottish maximum 14.8 mg/l, Irish minimum 19.08mg/l). In spite of this, my sedge-dominated communities, especially Group 5 *Schoenus* Springs, show floristic affinities to the *Eriophorum latifolium-Carex hostiana* Association.

The third sedge-dominated Scottish community, the *Carex panicea-Campylium stellatum* Association (Birks 1973) has the lowest pH and calcium levels, with a median pH value of 6.0 and a median calcium concentration of 3.1 mg/l. Thus, it falls well outside the range of the Irish samples in the present study. Nevertheless, it also shows floristic affinities to some of my groups: most closely related are Group 6 *Carex lepidocarpa* Small Sedge Springs and Group 7 *Palustriella falcata-Carex panicea* Springs.

Table 5.7: Water chemistry data and tufa formation notes for published plant community descriptions. Where individual values are given, they are summarised below as median, range and sample size.

Community	pH	Calcium mg/l	Tufa
Tufaceous Mounds, Tarn Moor (Holdgate 1955)	8.0 – 8.5	-	Tufa mounds up to 10m diameter
Open Flushes, Tarn Moor (Holdgate 1955)	7.5 - 8.5	-	Tufa granules
Gravel Flushes, Upr Teesdale (Pigott 1956)	-	-	Tufa hummocks 10-20cm
Bryophyte Flushes, Upr Teesdale (Pigott 1956)	6.8	27	-
Cratoneuron commutatum-Saxifraga aizoides nodum (McVean & Ratcliffe 1962)	7.3 7.3 – 7.4 (n=3)	38.87 22.77 – 49.03 (n=3)	'may have incipient tufa formation'
Cariceto-Saxifragetum aizoidis (McVean & Ratcliffe 1962)	6.8 6.8 – 7.2 (n=5)	9.05 5.28 – 13.03 (n=4)	Muds, usually calcareous, sometimes strongly so
Carex rostrata-brown moss nodum (McVean & Ratcliffe 1962)	6.8 6.5 – 6.8 (n=6)	12.56 8.31 – 19.80 (n=5)	-
Cratoneuron-Carex nodum (Eddy *et al.* 1969)	4.9 – 5.1	47 - 106	'a tendency to tufa formation in places'
Cratoneuron commutatum-Saxifraga aizoides nodum (Birks 1973)	7.1 6.8 – 7.4 (n=4)	8.5 7.6 – 9.6 (n=4)	'often incipient tufa-formation'
Eriophorum latifolium-Carex hostiana Association (Birks 1973)	6.8 6.4 – 7.2 (n=6)	8.4 7.0 – 14.8 (n=6)	-
Carex panicea-Campylium stellatum Association (Birks 1973)	6.0 5.6 – 6.2 (n=6)	3.1 2.4 – 3.6 (n=6)	-
'Short Fen' (Boyer & Wheeler 1989) (See Table 5.8 for additional chemical parameters)	7.25 7.05 – 7.38 (n=8)	113 97 – 146 (n=8)	Tufa deposits at two of the four sites sampled
Campylio-Caricetum dioicae (Ó Críodáin & Doyle 1994)	4.6 – 7.5	-	-
Schoenetum nigricantis (Ó Críodáin & Doyle 1997)	5.0 – 8.1	-	-
M10 *Carex dioica-Pinguicula vulgaris* mire (Rodwell 1998b)	5.5 – >7.0	up to 100	'often some deposition of tufa...which can...give the turf a very characteristic crunchy texture'
M13 *Schoenus nigricans-Juncus subnodulosus* mire (Rodwell 1998b)	6.5 – 8.0	60 – 200	

The *Cratoneuron-Carex* nodum (Eddy *et al.* 1969) has much lower water pH values (pH 4.9 – 5.1) than my Group 7 *Palustriella falcata-Carex panicea* Springs (7.41 - 11.38). The two communities overlap in floristic composition (see Section 4.2.7), but the constant presence of *Carex nigra, C. demissa* and *Philonotis fontana* in the former community suggest it is less calcicole than my Group 7 community and pH data confirm that this is the case.

Data from previous Irish studies suggest that the *Schoenetum nigricantis* (pH 5.0 – 8.1) and *Campylio-Caricetum dioicae* (pH 4.6 – 7.5) can form over very wide pH ranges (Ó Críodáin & Doyle 1994, 1997). My groups with the most similar vegetation are Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs. Group 5 *Schoenus* Springs (pH 7.04 – 8.19) fall within the upper part of the *Schoenetum nigricantis* range; Group 6 *Carex lepidocarpa* Small Sedge Springs (pH 7.29 – 8.25) overlap with the upper limit of the *Campylio-Caricetum dioicae* and extend well beyond its range.

Boyer & Wheeler (1989) provided more detailed water analysis for British 'Short-Fen' vegetation (alliance *Caricion davallianae* Klika 1934). In British Short-Fens, pH ranged from 7.05 to 7.38 with a median value of 7.25 (Table 5.8 below); these levels are somewhat lower than my Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs, the median values of which exceed the maximum value of the Short-Fen samples. Alkalinity levels for Short-Fens fall within the range of Groups 5 and 6, but calcium and magnesium concentrations are somewhat higher than in my samples. Nutrient levels are much higher in the Short-Fen samples; the median value for nitrate levels, 29.4 mg/l, is especially high, but it reflects elevated levels at one site only (two sites were omitted from nitrate analysis in Boyer and Wheeler's study). Sulphate levels are also high in the Short-Fen samples compared to my data.

Of the communities shown in Table 5.7 (above), the highest pH values were recorded in the Tufaceous Mounds (pH 8.0 – 8.5) and Open Flushes (pH 7.5 – 8.5) of Tarn Moor (Holdgate 1955). These habitats are sedge-dominated, apart from large mounds of *Philonotis fontana* at the springheads; they are clearly portrayed by the author as tufa-forming, with large springhead mounds of tufa up to 10m in diameter and 50 – 75cm in height. The mounds are interspersed by stony flushes, with soft calcareous mud and 'tufa granules'. There are no good analogues for this mound and flush mosaic amongst my groups: Group 5 *Schoenus* Springs, Group 6 *Carex lepidocarpa* Small Sedge Springs and Group 7 *Palustriella falcata-Carex panicea* Springs have some floristic affinities especially amongst sedge species (Sørensen coefficients of similarity 27% to 41%), but their physiognomy is different. The Tarn Moor pH values, however, are on the whole higher than values for Groups 5, 6 and 7; they are closer to those of my bryophyte-dominated Groups 1 to 4 which are also my most strongly tufa-forming groups.

Table 5.8: Water analysis (median and range) from British 'Short-Fens' (*Caricion davallianae*; Boyer & Wheeler 1989) compared with my Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs

	British *Caricion davallianae* 'Short Fen' n=8 (except for NO_3^- n=5)	**Group 5 *Schoenus* Springs** n=12	**Group 6 *C. lepidocarpa* Small Sedge Springs** n=17
pH	7.25 7.05 – 7.38	7.61 7.04 - 8.19	7.76 7.29 - 8.25
HCO_3^- mg/l	379 285 - 406	334 199 - 484	328 157 - 431
Ca^{2+} mg/l	113 97 - 146	92.21 57.34 - 129.36	103.02 40.90 - 125.57
Mg^{2+} mg/l	34 3 - 53	10.52 1.10 - 19.43	10.39 1.42 - 29.28
K^+ mg/l	2.3 1.4 – 3.0	0.49 0.14 - 6.39	0.97 0.16 - 8.92
NO_3^- mg/l	29.4 0.85 – 32.0	<0.07 <0.07 - 8.44	0.65 <0.07 - 64.70
PO_4^{3-} µg/l	18 <15 – 92	6 3 - 59	16 2 - 29
SO_4^{2-} mg/l	68 17 - 211	5.53 <0.06 - 23.82	13.57 1.02 - 45.71

Pentecost (2005) reports water analysis data for Güterstein Waterfall where two of my German relevés were recorded. My German samples, on the whole, have the strongest floristic, tufa-forming and hydrological affinities with Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes and, to a lesser extent, Group 2 *Palustriella commutata-Geranium robertianum* Springheads. Water analysis for these groups (and the full Irish data set) is shown in Table 5.9 along with Pentecost's Güterstein data.

Table 5.9: Comparison of water analysis from Güterstein Waterfall (Pentecost 2005) with Irish spring water in Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Flushes, Group 2 *Palustriella commutata-Geranium robertianum* Springheads and the full Irish petrifying spring water sample data set. Data are median values.

	Güterstein	**Group 3**	**Group 2**	**Irish (all)**
n	nd	14	17	111 to 115
pH	7.18	7.93	8.06	7.97
HCO_3^- mg/l	291	326	303	293
Ca^{2+} mg/l	112.2	113.44	88.64	84.5
Mg^{2+} mg/l	1.46	7.76	6.18	8.15
K^+ mg/l	0.39	2.11	1.07	0.91
Na^+ mg/l	4.83	12.62	9.62	8.97
SO_4^{2-} mg/l	51.87	15.42	6.48	8.28

nd = no data provided

Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes are similar in the chemical composition of their waters to that of Güterstein. The pH at Güterstein is somewhat lower than the median value for Group 3, but it is within the range for this group (7.00 – 8.30, Table 5.6 above). Alkalinity levels are similar in both cases and calcium values are almost identical. Güterstein water has somewhat lower concentrations of magnesium, potassium and sodium. Sulphate levels are considerably higher than the Group 3 median value, and they are at the upper end of the Group 3 range. (Group 3 contains the two outlying sulphate values of 142 and 147 mg/l; apart from these, the highest Group 3 value is 42.67 mg/l.)

5.2.3 NMS Ordination

The relationship between water analysis data and the NMS ordination of relevés (Chapter 3) is illustrated in Figs 5.6, 5.7 and 5.8 (produced in PC-ORD) as joint plots of chemical parameters overlying plant communities. PC-ORD calculates correlations using Pearson's product-moment method, which assumes that the data are normally distributed. Several of my water analysis parameters do not meet this assumption (Fig. 5.2). Correlations were therefore calculated separately using Spearman's rank correlation method, which does not assume distributions are normal (see Table 5.10 and Fig. 5.9).

An additional issue arose in calculating the joint plots in Figs 5.6 to 5.8. Twenty-three of the relevés contained in the original NMS ordination in Chapter 3 (Figs. 3.10 to 3.16) are not represented in the water analysis data set. This is problematic for computing joint plots as PC-ORD does not permit data sets to contain missing values. One way of overcoming this is to insert mean or median values for the missing data (McCune and Grace 2002). In Figs 5.6 to 5.8, fuzzy cluster group median values were inserted for each missing value for water analysis in the PC-ORD data set. (The joint plot using group means to replace missing values was also inspected; the use of median values resulted in a slightly better representation of the significant relationships in Table 5.10).

Thus, the ordination joint plots in Figs 5.6 to 5.8 provide a useful aid for visualising the relationships of chemical parameters with plant communities and other abiotic variables such as tufa type, but they should be read in conjunction with Table 5.10 and Fig. 5.9.

NMS Axis 1 is correlated negatively with pH and positively with alkalinity levels, in keeping with the inverse relationship of these parameters shown in Figs 5.3 and 5.5. The correlation between Axis 1 and pH is stronger than with alkalinity as shown by the r_s values in Table 5.10 and the length of the radiating lines in Figs 5.6. Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs, with the lowest pH values, have the highest scores on Axis 1.

The nutrients nitrate and phosphate decrease along Axis 2 and increase along Axis 3 representing the contrast between the higher nutrient levels in Groups 1 – 3 compared to Groups 5 – 8. The strongest relationship in Table 5.10 is between Axis 3 and phosphate (r_s = 0.530). Figs. 5.7 to 5.9 show phosphate levels increasing towards Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes, the community with the highest Axis 3 scores. This community has somewhat higher phosphate levels than other groups (Fig. 5.4). The Group 3 sample with the highest concentration of phosphate, WS139 containing 991 µg/l phosphate, was treated as an outlier (see Section 5.2.1 above); it was replaced in the NMS data set by the median

value. Even so, the NMS joint plot shows a relatively strong correlation between Axis 3 and phosphate levels and this is confirmed by the r_s value.

Water chemistry variables are less strongly correlated with the NMS axes than the environmental variables (such as slope, tufa type and tree canopy cover) discussed in Chapter 3. On the whole water chemistry parameters have shorter radiating lines on the NMS joint plots and lower r_s values (Table 5.10 compared with Table 3.12). (Joint plot vectors in Figs 5.6 to 5.8 are drawn at a larger scale than in Figs. 3.13 to 3.15 (x 1.45) to accommodate labels.)

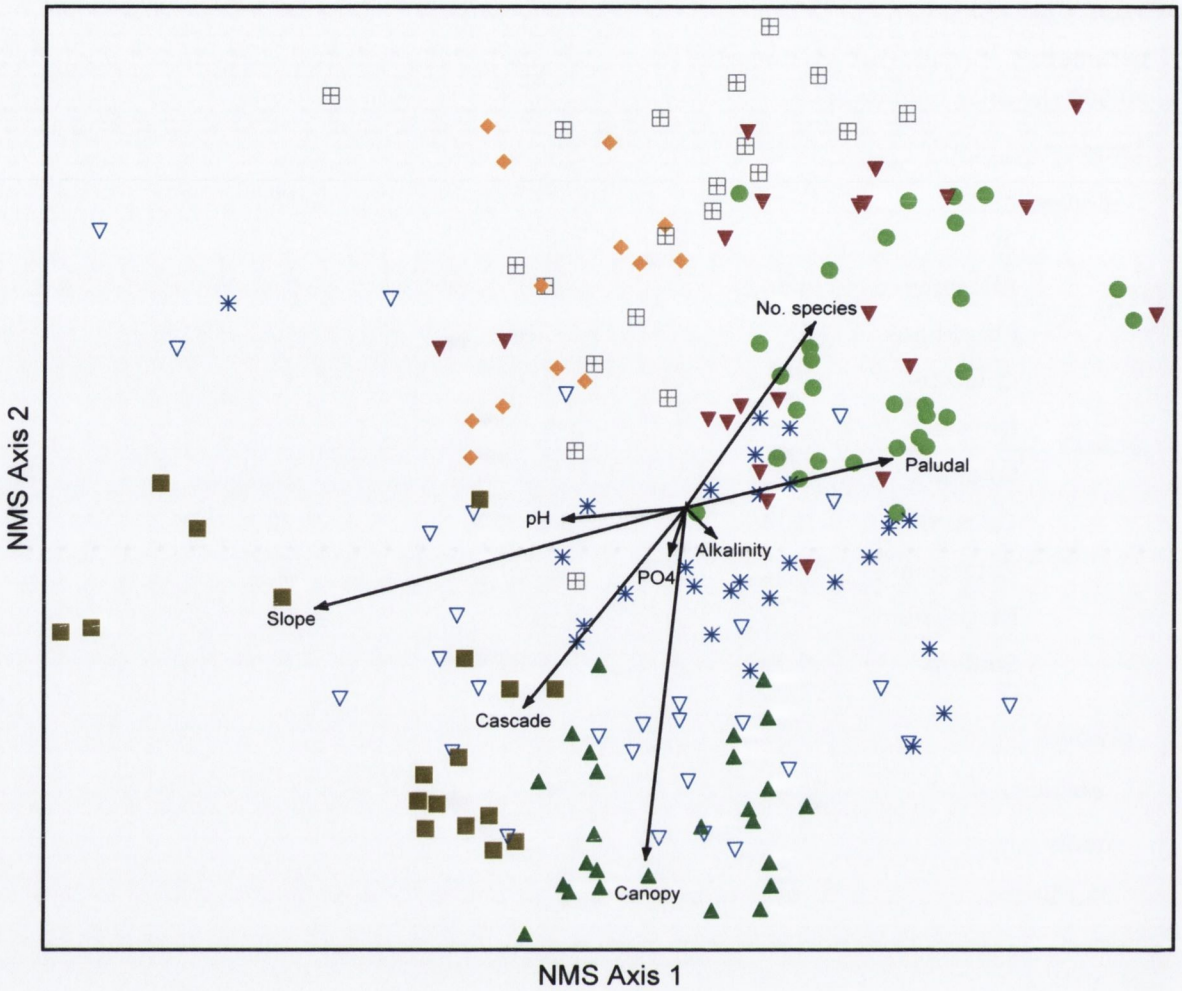
NMS ordinations of species with water chemistry variables are shown in Figs 5.10 to 5.12. Clearly, non-chemical parameters exert a strong influence here; for example, woodland species predominate as tree canopy cover increases. Nevertheless, it is worth noting the position of species relative to the two chemical parameters with the strongest correlations to axes, phosphate with Axis 3 and pH with Axis 1.

Nasturtium officinale, Apium nodiflorum, Ranunculus repens, R. acris, Potentilla reptans, Glyceria notata, Platyhypnidium riparioides, Brachythecium rivulare and *Cratoneuron filicinum* coincide with the highest phosphate concentrations towards the upper end of Axis 3. Conversely, where phosphate levels are lowest on the ordination diagram, species such as *Pinguicula lusitanica, P. grandiflora, P. vulgaris, Anagallis tenella, Drosera rotundifolia, Schoenus nigricans, Carex hostiana, Isolepis cernua, Eleocharis quinqueflora, Selaginella selaginoides* and *Scorpidium scorpioides* are found.

In the part of the ordination where pH levels are at their highest, *Plantago maritima, Eucladium verticillatum, Didymodon tophaceus* and *Pellia endiviifolia* are located. The density of species on the ordination is much greater towards the lower end of the range of pH levels than at the upper end; species coinciding with the lower part of the pH range include *Pedicularis palustris, Hydrocotyle vulgaris, Galium uliginosum, Menyanthes trifoliata, Phragmites australis, Juncus subnodulosus, Carex nigra* and *C. rostrata*.

Table 5.10: Spearman rank correlation coefficients (r_s) for NMS ordination axes and chemical parameters. P-values are corrected by Dunn-Šidák method for multiple comparisons. Value for r_s >0.500 shown in bold type.

	Axis 1		Axis 2		Axis 3	
pH	-0.480	***	-0.239		0.162	
Alkalinity	0.340	***	-0.208		0.171	
Phosphate	0.024		-0.383	***	**0.530**	***
Chloride	0.038		-0.041		-0.061	
Nitrate	-0.092		-0.445	***	0.323	***
Sulphate	-0.022		-0.171		0.221	
Calcium	0.243		-0.190		0.206	
Potassium	-0.029		-0.256	*	0.159	
Magnesium	0.278	**	-0.094		-0.130	
Sodium	-0.039		-0.078		-0.099	



Plant Communities (Fuzzy Cluster Groups)

- Gr. 1: E. verticillatum-P. endiviifolia Tufa Cascades
- Gr. 2: P. commutata-G. robertianum Springheads
- Gr. 3: B. rivulare-P. riparioides Streams/Flushes
- Gr. 4: P. commutata-A. stolonifera Springheads
- Gr. 5: Schoenus Springs
- Gr. 6: C. lepidocarpa Small Sedge Springs
- Gr. 7: P. falcata-C. panicea Springs
- Gr. 8: S. aizoides-S. oelandica Springs

Fig. 5.6: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities (Chapter 3) and correlated chemical and environmental variables (Pearson product-moment correlation $r^2 > 0.05$; see Fig. 5.9 for alternative Spearman rank correlations).

Variance (r^2) values of axes: Axis 1 = 0.216 Axis 2 = 0.303.

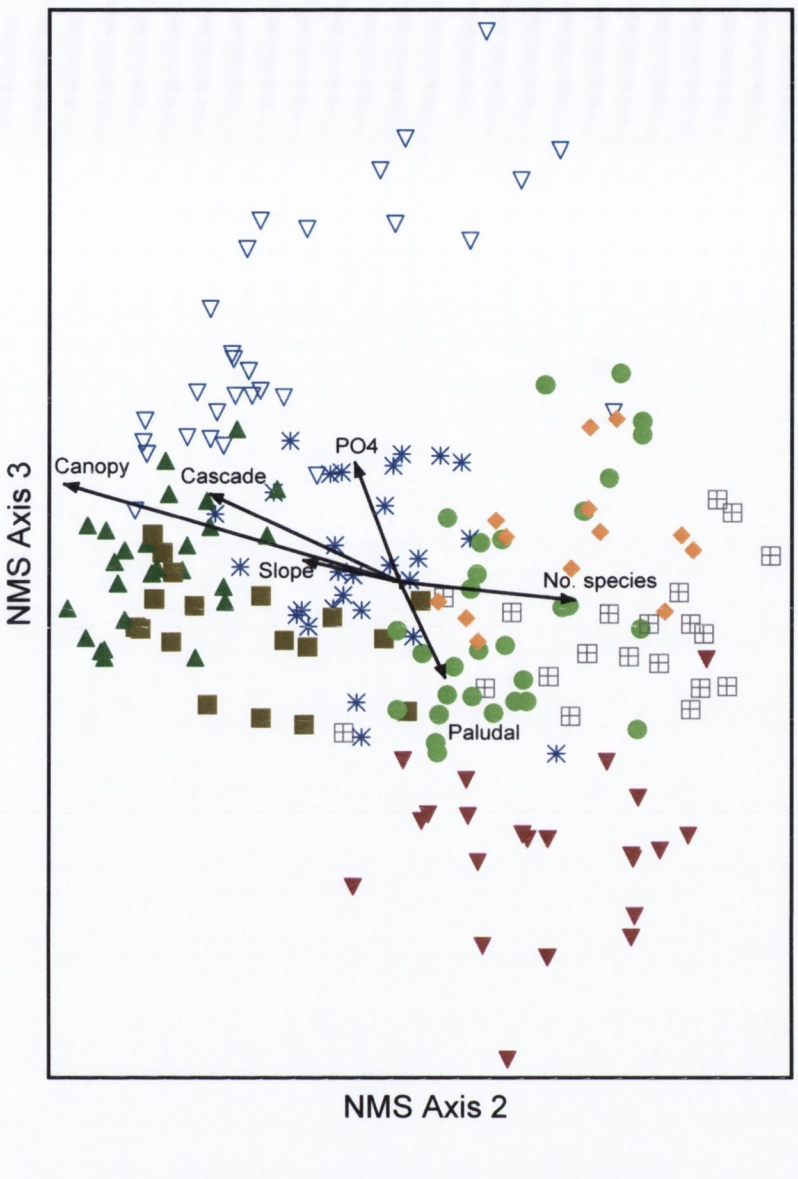


Fig. 5.7: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities (Chapter 3) and correlated chemical and environmental variables (Pearson product-moment correlation $r^2>0.05$; see Fig. 5.9 for alternative Spearman rank correlations).

Variance (r^2) values of axes: Axis 2 = 0.303 Axis 3 = 0.268

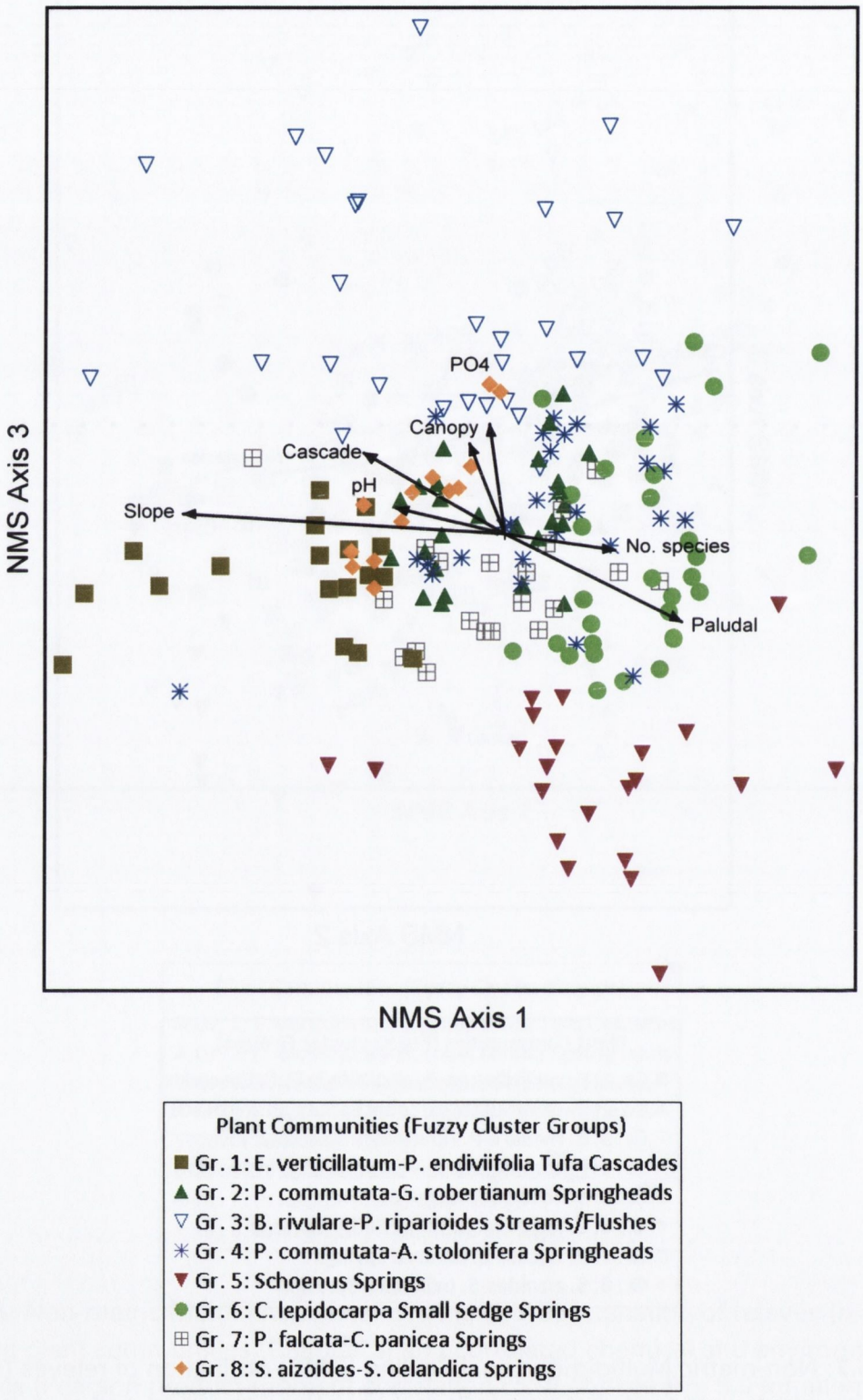


Fig. 5.8: Non-metric Multidimensional Scaling (NMS) ordination of relevés (n=186) showing plant communities (Chapter 3) and correlated chemical and environmental variables (Pearson product-moment correlation $r^2>0.05$; see Fig. 5.9 for alternative Spearman rank correlations).

Variance (r^2) values of axes: Axis 1 = 0.216 Axis 3 = 0.268

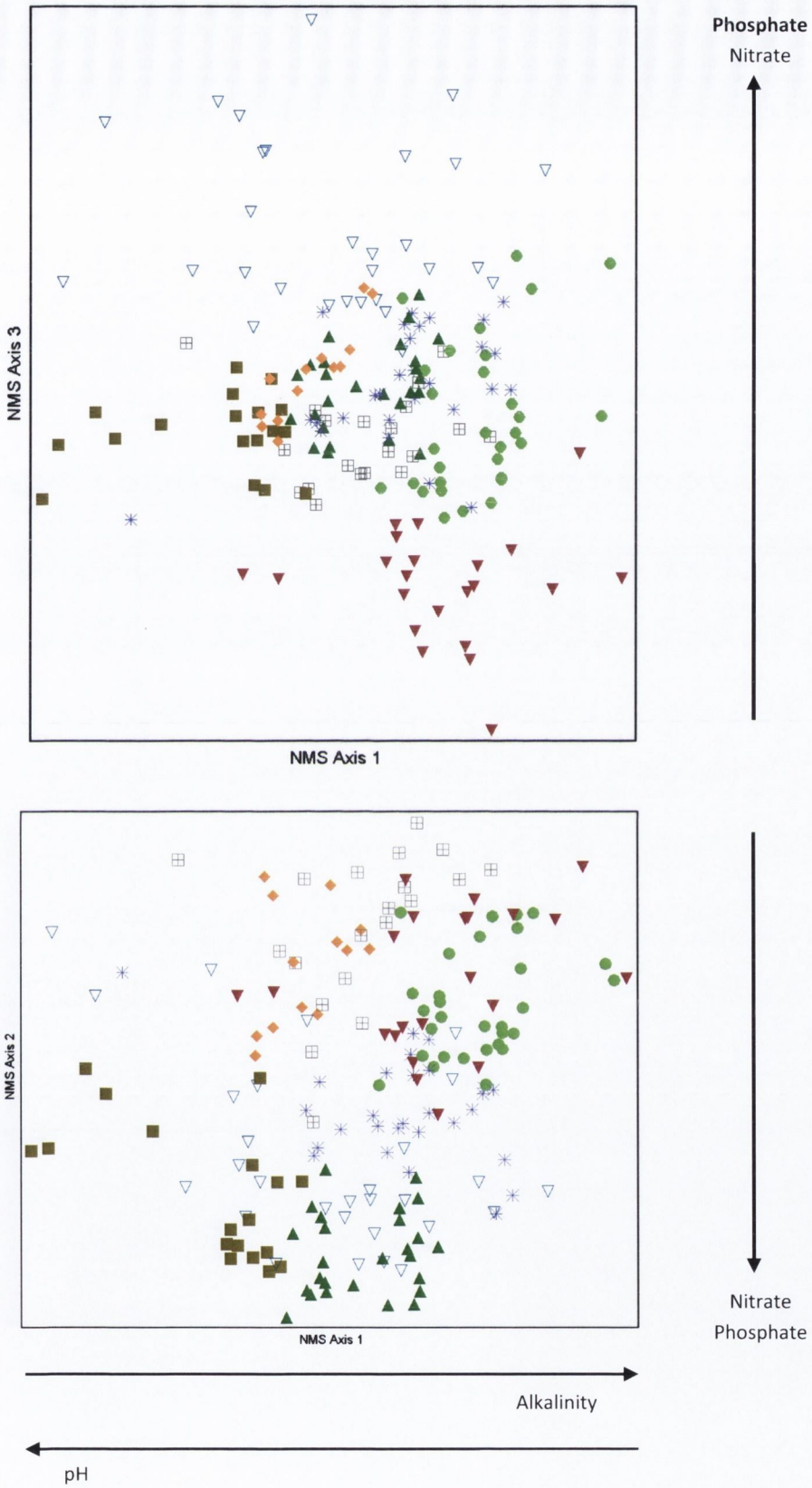


Fig. 5.9: Relationship between NMS ordination and chemical composition of springwater, calculated by Spearman rank correlation coefficients, $p<0.001$. Variable in bold type has $r_s > 0.5$ (see Table 5.10 above). Plant community symbols as in Fig 5.8 above.

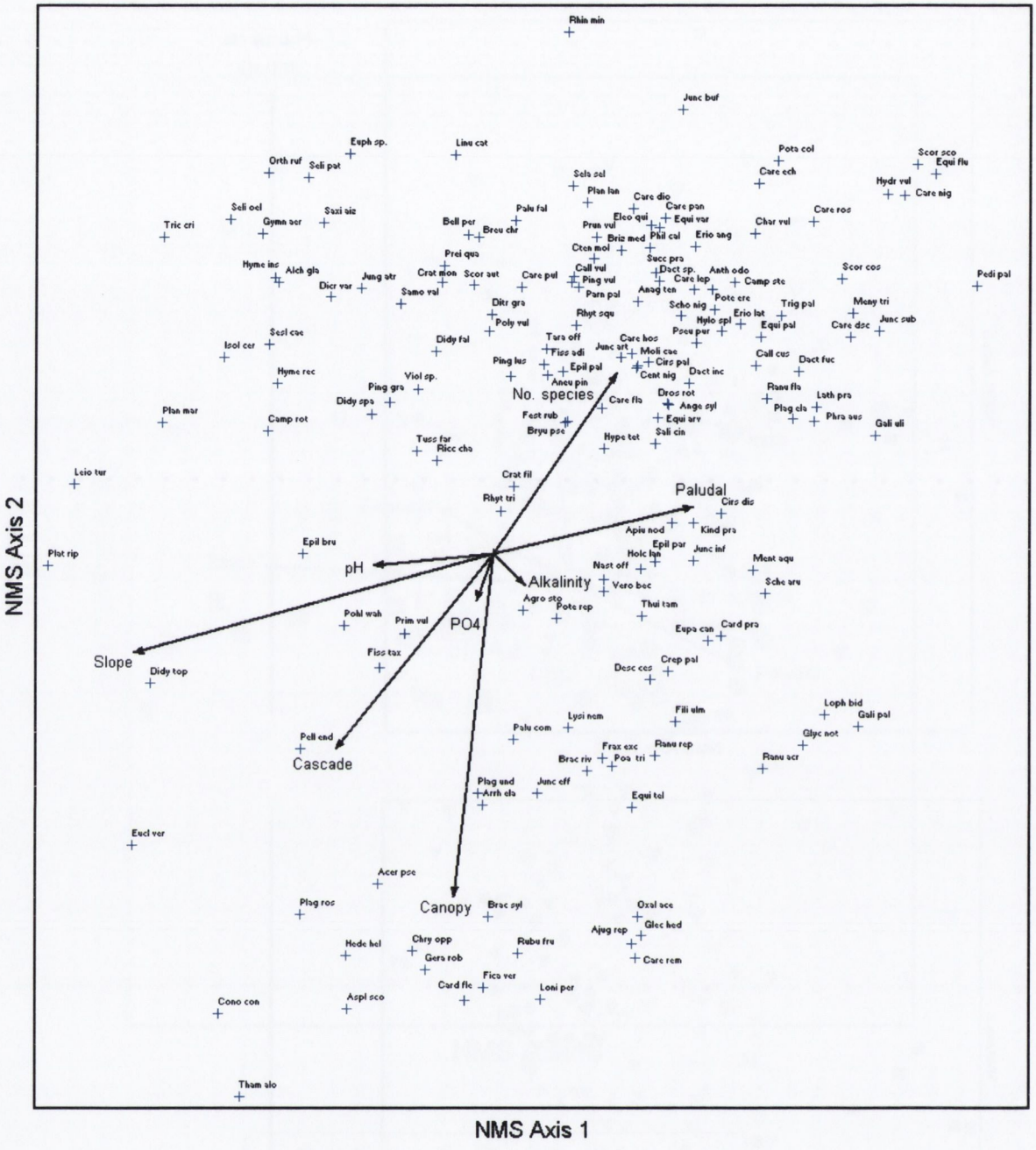


Fig. 5.10: NMS ordination of species (Axes 1 and 2) showing correlated chemical and environmental variables. See Table 5.11 below for list of abbreviated species names.



Fig. 5.11: NMS ordination of species (Axes 2 and 3) showing correlated chemical and environmental variables. See Table 5.11 below for list of abbreviated species names.

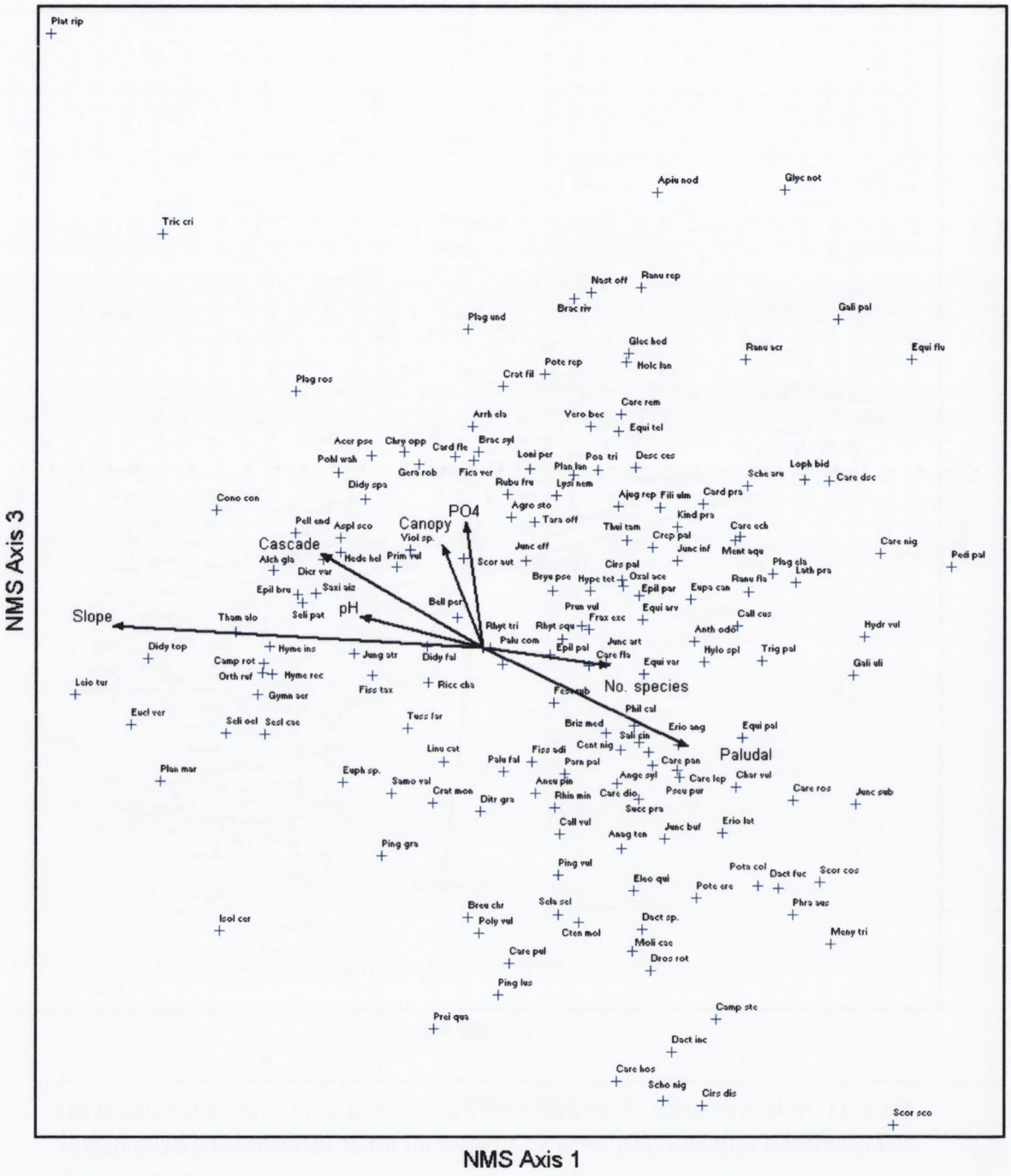


Fig. 5.12: NMS ordination of species (Axes 1 and 3) showing correlated chemical and environmental variables. See Table 5.11 below for list of abbreviated species names.

Table 5.11: Abbreviations of species names in Figs 5.10 to 5.12 above

Acer pse	Acer pseudoplatanus	Eleo qui	Eleocharis quinqueflora	Palu fal	Palustriella falcata
Agro sto	Agrostis stolonifera	Epil bru	Epilobium brunnescens	Parn pal	Parnassia palustris
Ajug rep	Ajuga reptans	Epil pal	Epilobium palustre	Pedi pal	Pedicularis palustris
Alch gla	Alchemilla glabra	Epil par	Epilobium parviflorum	Pell end	Pellia endiviifolia
Anag ten	Anagallis tenella	Equi arv	Equisetum arvense	Phil cal	Philonotis calcarea
Aneu pin	Aneura pinguis	Equi flu	Equisetum fluviatile	Phra aus	Phragmites australis
Ange syl	Angelica sylvestris	Equi pal	Equisetum palustre	Ping gra	Pinguicula grandiflora
Anth odo	Anthoxanthum odoratum	Equi tel	Equisetum telmateia	Ping lus	Pinguicula lusitanica
Apiu nod	Apium nodiflorum	Equi var	Equisetum variegatum	Ping vul	Pinguicula vulgaris
Arrh ela	Arrhenatherum elatius	Erio ang	Eriophorum angustifolium	Plag ela	Plagiomnium elatum
Aspl sco	Asplenium scolopendrium	Erio lat	Eriophorum latifolium	Plag ros	Plagiomnium rostratum
Bell per	Bellis perennis	Eucl ver	Eucladium verticillatum	Plag und	Plagiomnium undulatum
Brac riv	Brachythecium rivulare	Eupa can	Eupatorium cannabinum	Plan lan	Plantago lanceolata
Brac syl	Brachypodium sylvaticum	Euph sp.	Euphrasia sp.	Plan mar	Plantago maritima
Breu chr	Breutelia chrysocoma	Fest rub	Festuca rubra	Plat rip	Platyhypnidium riparioides
Briz med	Briza media	Fica ver	Ficaria verna	Poa tri	Poa trivialis
Bryu pse	Bryum pseudotriquetrum	Fili ulm	Filipendula ulmaria	Pohl wah	Pohlia wahlenbergii
Call cus	Calliergonella cuspidata	Fiss adi	Fissidens adianthoides	Poly vul	Polygala vulgaris
Call vul	Calluna vulgaris	Fiss tax	Fissidens taxifolius	Pota col	Potamogeton coloratus
Camp rot	Campanula rotundifolia	Frax exc	Fraxinus excelsior	Pote ere	Potentilla erecta
Camp ste	Campylium stellatum	Gali pal	Galium palustre	Pote rep	Potentilla reptans
Card fle	Cardamine flexuosa	Gali uli	Galium uliginosum	Prei qua	Preissia quadrata
Card pra	Cardamine pratensis	Gera rob	Geranium robertianum	Prim vul	Primula vulgaris
Care dio	Carex dioica	Glec hed	Glechoma hederacea	Prun vul	Prunella vulgaris
Care dsc	Carex disticha	Glyc not	Glyceria notata	Pseu pur	Pseudoscleropodium purum
Care ech	Carex echinata	Gymn aer	Gymnostomum aeruginosum	Ranu acr	Ranunculus acris
Care fla	Carex flacca	Hede hel	Hedera helix	Ranu fla	Ranunculus flammula
Care hos	Carex hostiana	Holc lan	Holcus lanatus	Ranu rep	Ranunculus repens
Care lep	Carex lepidocarpa	Hydr vul	Hydrocotyle vulgaris	Rhin min	Rhinanthus minor
Care nig	Carex nigra	Hylo spl	Hylocomium splendens	Rhyt squ	Rhytidiadelphus squarrosus
Care pan	Carex panicea	Hyme rec	Hymenostylium recurvirostrum	Rhyt tri	Rhytidiadelphus triquetrus
Care pul	Carex pulicaris	Hyme ins	H. recurvirostrum var insigne	Ricc cha	Riccardia chamedryfolia
Care rem	Carex remota	Hype tet	Hypericum tetrapterum	Rubu fru	Rubus fruticosus
Care ros	Carex rostrata	Isol cer	Isolepis cernua	Sali cin	Salix cinerea
Cent nig	Centaurea nigra	Junc art	Juncus articulatus	Samo val	Samolus valerandi
Char vul	Chara vulgaris	Junc buf	Juncus bufonius agg.	Saxi aiz	Saxifraga aizoides
Chry opp	Chrysosplenium oppositifolium	Junc eff	Juncus effusus	Sche aru	Schedonorus arundinaceus
Cirs dis	Cirsium dissectum	Junc inf	Juncus inflexus	Scho nig	Schoenus nigricans
Cirs pal	Cirsium palustre	Junc sub	Juncus subnodulosus	Scor aut	Scorzoneroides autumnalis
Cono con	Conocephalum conicum agg.	Jung atr	Jungermannia atrovirens	Scor cos	Scorpidium cossonii
Crat fil	Cratoneuron filicinum	Kind pra	Kindbergia praelonga	Scor sco	Scorpidium scorpioides
Crat mon	Crataegus monogyna	Lath pra	Lathyrus pratensis	Sela sel	Selaginella selaginoides
Crep pal	Crepis paludosa	Leio tur	Leiocolea turbinata	Seli oel	Seligeria oelandica
Cten mol	Ctenidium molluscum	Linu cat	Linum catharticum	Seli pat	Seligeria patula
Dact fuc	Dactylorhiza fuchsii	Loni per	Lonicera periclymenum	Sesl cae	Sesleria caerulea
Dact inc	Dactylorhiza incarnata	Loph bid	Lophocolea bidentata	Succ pra	Succisa pratensis
Dact sp.	Dactylorhiza sp.	Lysi nem	Lysimachia nemorum	Tara off	Taraxacum officinale agg.
Desc ces	Deschampsia cespitosa	Ment aqu	Mentha aquatica	Tham alo	Thamnobryum alopecurum
Dicr var	Dicranella varia	Meny tri	Menyanthes trifoliata	Thui tam	Thuidium tamariscinum
Didy fal	Didymodon fallax	Moli cae	Molinia caerulea	Tric cri	Trichostomum crispulum
Didy spa	Didymodon spadiceus	Nast off	Nasturtium officinale agg.	Trig pal	Triglochin palustris
Didy top	Didymodon tophaceus	Orth ruf	Orthothecium rufescens	Tuss far	Tussilago farfara
Ditr gra	Ditrichum gracile	Oxal ace	Oxalis acetosella	Vero bec	Veronica beccabunga
Dros rot	Drosera rotundifolia	Palu com	Palustriella commutata	Viol sp.	Viola sp.

5.2.4 Species Ecology and Spring Water Composition

Bryophytes

Habitat preferences of *Palustriella commutata* and *P. falcata* were investigated by Bell & Lodge (1963) and Hedenäs & Kooijman (2004); these studies were not confined to petrifying springs, but took in the broader habitat range of these species. In both studies, *P. falcata* was found to have a wider habitat range than *P. commutata*. Both species were found at high pH values (up to approximately pH 8.1), but the range of *P. falcata* extended to much lower values and the mean was significantly lower (Hedenas & Kooijman 2004). *P. falcata* also occurred across a wider range of calcium and bicarbonate concentrations than *P. commutata*, while the nitrate levels were significantly higher for *P. commutata* (mean 5.5mg/l compared to 1.1mg/l, $p<0.05$). The water analysis data of Bell and Lodge for these two species, collected from 30 sites in Scotland and England, are plotted alongside my Irish data in Fig. 5.13. Even for these characteristic *Cratoneurion* species, petrifying springs represent the extreme upper end of their pH range; in spite of the large number of samples in my study, especially for *P. commutata* (n=86), the pH ranges of the two studies barely overlap. While there is no significant difference between the composition of spring water in which the two species are found within Irish petrifying springs, there is a highly significant difference between the water composition of Bell and Lodge's samples compared to my samples, not just for pH, but for each of calcium, magnesium and sodium (Wilcoxon signed rank tests, $p<0.0001$, corrected by Dunn Šidák method for multiple comparisons). Fig. 5.13 shows the higher levels of these parameters in Irish petrifying springs (with outliers removed as per Table 5.3). Water composition at sites in the Swedish study of these two species (Hedenäs and Kooijman 2004) is more similar to that of Irish sites. The ranges reported there for pH, calcium and alkalinity overlap with the range of my Irish samples; values for *P. commutata* fall within the range in my study but those of *P. falcata* are slightly lower, being intermediate between my petrifying spring data and those of Bell and Lodge from Britain.

The pH and alkalinity ranges of ecologically distinctive bryophyte species are shown in Fig. 5.14, which illustrates the gradient of pH and alkalinity within *Cratoneurion* vegetation, moving from the high pH spring waters of the specialist *Saxifragetum aizoidis* communities in the Benbulbin Range, through the steep *Adiantion*-type tufa cascades and then into the rich-fen, paludal tufa-forming communities of level ground. The taxa *Seligeria oelandica, Hymenostylium recurvirostrum* var. *insigne, H. recurvirostrum* var. *recurvirostrum* and *Orthothecium rufescens*, occurring in my Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs, occur in spring waters with the highest median pH values (8.25 – 8.32) and with very narrow pH ranges. Springs in which *Eucladium verticillatum, Didymodon tophaceus* and *Pellia endiviifolia* are found also have high

median pH values (8.07) and relatively narrow pH ranges. These species are characteristic of steep tufa cascades, indicative of both *Cratoneurion* and *Adiantion* vegetation types. *Palustriella commutata* occurs in spring waters with a median pH value of 8.02 and a somewhat wider pH range than the above named species; thus, in terms of its pH range, it lies between the springs related to *Adiantion* communities on the one hand, and those approaching rich-fen *Caricion davallianae* communities on the other. The latter communities typically contain the species *Aneura pinguis, Philonotis calcarea, Bryum pseudotriquetrum, Calliergonella cuspidata, Palustriella falcata, Campylium stellatum, Scorpidium cossonii* and *S. scorpioides*. Their pH values have, on the whole, broader ranges than the previously named species; their median values range from 7.1 to 8.01.

The alkalinity levels associated with these species again show an inverse pattern to that of pH. Median alkalinity levels for the specialist bryophytes of Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs (numbered 1 to 4 in Fig. 5.14) are 160.2 – 191.7 mg/l HCO_3^-, those for *Eucladium verticillatum, Didymodon tophaceus* and *Pellia endiviifolia* are 263.0 – 285.5 mg/l HCO_3^-, the median alkalinity level of *Palustriella commutata* spring waters is 292.8 mg/l HCO_3^-, and the median values of the paludal tufa, rich-fen species (numbered 9 to 16 in Fig. 5.14) are 242.7 – 356.5 mg/l HCO_3^-.

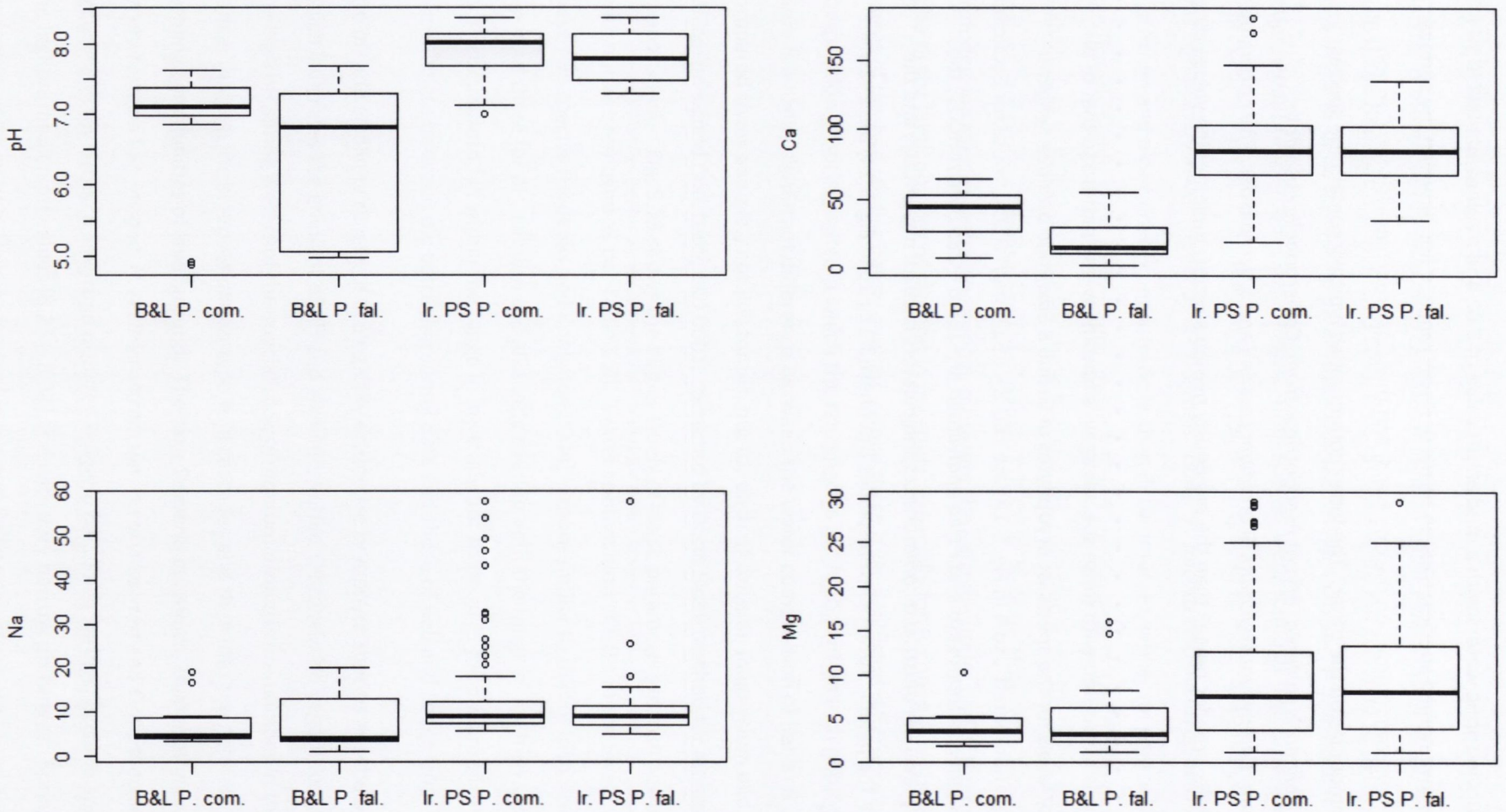
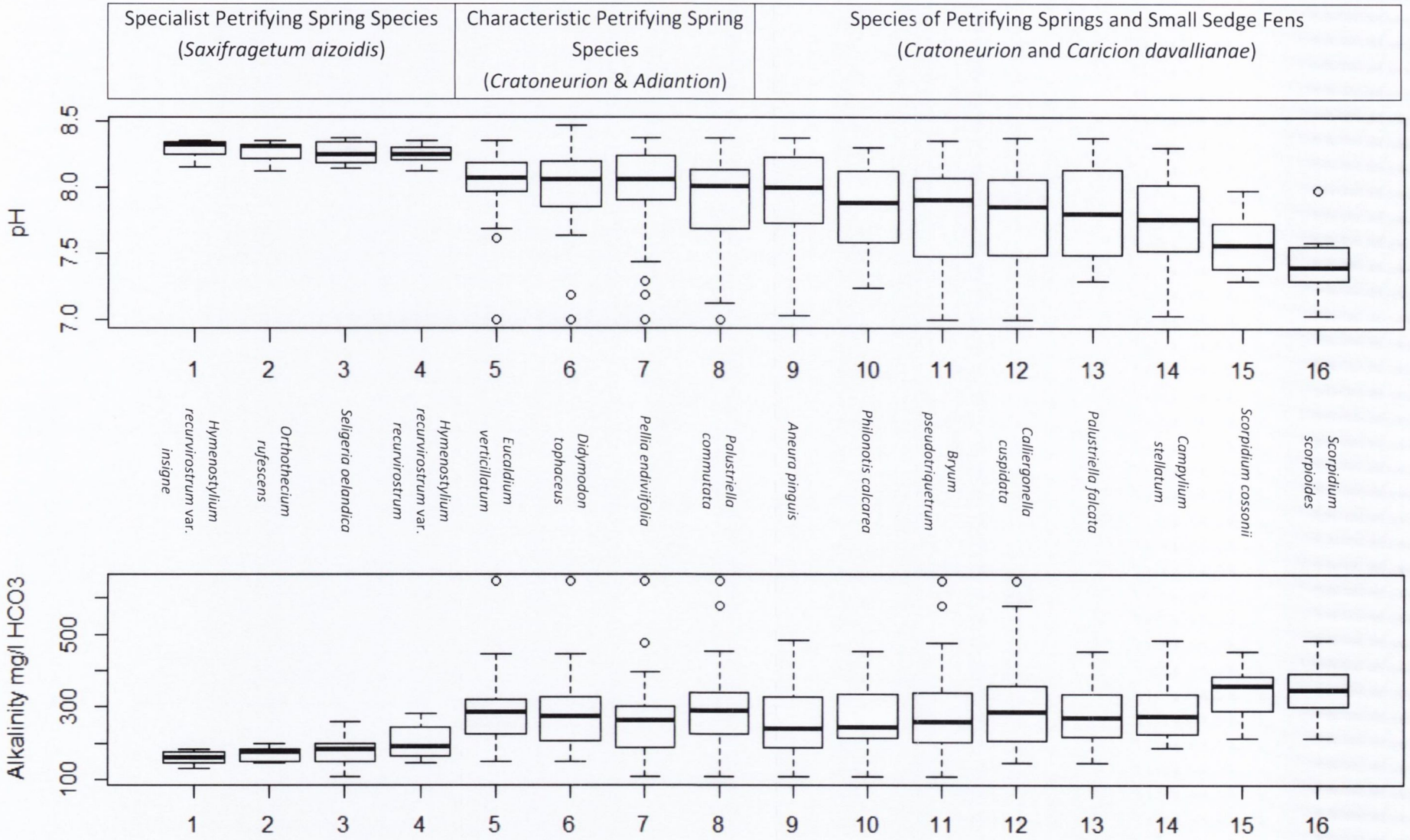


Fig. 5.13: Comparison of water analysis data collected by Bell & Lodge (1963) for *Palustriella commutata* and *P. falcata* with data from Irish petrifying springs collected during the present study. B&L P. com. = Bell & Lodge *P. commutata* (n=13); B&L P. fal. = Bell & Lodge *P. falcata* (n=18); Ir. PS P. com. = Irish petrifying springs *P. commutata* (n=86); Ir. PS P. fal. = Irish petrifying springs *P. falcata* (n=29).

Fig. 5.14: Box plots for ecologically distinctive bryophyte species of Irish petrifying springs arranged in descending order of pH. Heavy lines are median pH values, boxes are interquartile ranges, whiskers are maximum and minimum values excluding outliers, which are shown by circles.



The mean phosphate levels of the spring waters in which these (and some additional) species occur are plotted against pH in Fig. 5.15 below; pH values are calculated as geometric means. Group 8 bryophytes, such as *Seligeria oelandica, S. patula, Hymenostylium recurvirostrum* var. *insigne* and *Orthothecium rufescens*, are clustered at high pH and very low phosphate levels (7 - 8 µg/l PO_4^{3-}, Table 5.12). *Jungermannia atrovirens* occurs at the same phosphate level as these species but with a slightly lower mean pH of 8.17; this species was constant in the Benbulbin samples, but it is not confined geographically to that area. *Catoscopium nigritum*, *Leiocolea bantriensis* and *Tomentypnum nitens* all occurred at very low phosphate concentrations (4 – 7 µg/l PO_4^{3-}); the first two species were at pH values of 7.98 and 7.97 respectively, while *T. nitens* was at the lower pH of 7.39. *C. nigritum* and *T. nitens* data are single samples only; *L. bantriensis* was present at two water sampling locations. Several rich-fen species are clustered in the central part of the graph: *Campylium stellatum, Calliergonella cuspidata, Bryum pseudotriquetrum, Palustriella falcata, Philonotis calcarea, Fissidens adianthoides* and *Aneura pinguis* occurred at mean pH values close to 7.8 and phosphate concentrations of 0.010 – 0.013 mg/l. At slightly lower pH but higher phosphate levels, are *Scorpidium cossonii* and *S. scorpioides*, which sometimes co-occur with the species of the rich-fen cluster, but in the present study were found in spring waters with mean pH values of 7.58 and 7.44 and mean phosphate levels of 15 and 18 µg/l PO_4^{3-} respectively. At comparable phosphate levels to these two species, but at the upper end of the pH range, are *Palustriella commutata, Pellia endiviifolia, Eucladium verticillatum* and *Didymodon tophaceus,* clustered around pH 8.0 and phosphate concentrations of 16 – 18 µg/l PO_4^{3-}. The species occurring with the highest mean phosphate concentration in Fig. 5.15 is *Cratoneuron filicinum* (24 µg/l PO_4^{3-}, mean pH7.82). The mean phosphate level at which this species was recorded differs from that of *P. commutata* at $P<0.05$ (Wilcoxon rank test).

Fig. 5.15 represents only the lowest part of the phosphate range recorded in Irish petrifying springs during the present survey (although all but 13 samples (11%) fell within this part of the range). Fig. 5.16 shows the same species in the context of a wider range of phosphate levels. The mosses *Brachythecium rivulare* and *Platyhypnidium riparioides* occurred at very much higher mean phosphate levels, 0.067 and 219 µg/l PO_4^{3-} respectively. Both species were present at the location of WS139, the sample with the highest phosphate level. The mean levels for these two species are strongly influenced by this sample (*B. rivulare* less so due to a larger sample size, Table 5.13); both were thriving on the tufa cascade where the water sample was collected. The median value for *B. rivulare* (20 µg/l PO_4^{3-}) places it within the range shown on Fig. 5.15, but this is not the case for *P. riparioides*. With a median value of 75 µg/l PO_4^{3-}, its range is distinctly eutrophic compared to the other bryophyte species of Fig. 5.15.

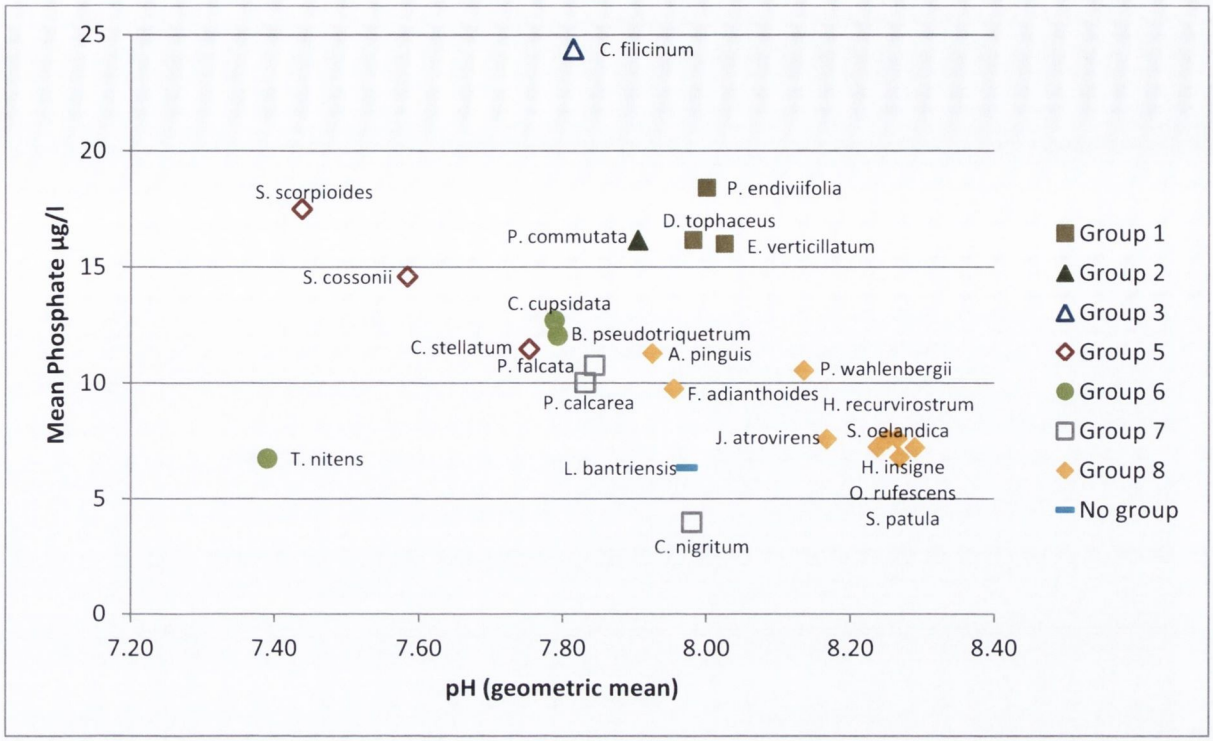


Fig. 5.15: mean pH and phosphate levels for selected bryophyte species at low phosphate levels.

Table 5.12: pH and phosphate values for bryophyte species shown in Fig. 5.15 above.

Species	n	pH			Phopshate µg/l		Plant
		Geometric Mean	Min	Max	Mean	SD	Community
Aneura pinguis	38	7.92	7.04	8.38	0.011	0.010	8
Bryum pseudotriquetrum	48	7.79	7.00	8.35	0.012	0.010	6
Calliergonella cuspidata	49	7.79	7.00	8.38	0.013	0.007	6
Campylium stellatum	25	7.75	7.04	8.30	0.011	0.012	5
Catoscopium nigritum	1	7.98	-	-	0.004	-	7
Cratoneuron filicinum	33	7.82	7.00	8.30	0.024	0.029	3
Didymodon tophaceus	22	7.98	7.00	8.47	0.016	0.013	1
Eucladium verticillatum	29	8.03	7.00	8.35	0.016	0.012	1
Fissidens adianthoides	19	7.95	7.34	8.34	0.010	0.007	8
Hymenostylium insigne	6	8.29	8.16	8.35	0.007	0.002	8
Hymenostylium recurvirostrum	8	8.25	8.13	8.35	0.008	0.003	8
Jungermannia atrovirens	12	8.17	7.86	8.35	0.008	0.003	8
Leiocolea bantriensis	2	7.97	7.79	8.16	0.006	0.001	No Group
Orthothecium rufescens	7	8.27	8.13	8.35	0.007	0.003	8
Palustriella commutata	85	7.90	7.00	8.38	0.016	0.019	2
Palustriella falcata	28	7.84	7.29	8.38	0.011	0.009	7
Pellia endiviifolia	48	8.00	7.00	8.38	0.018	0.025	1
Philonotis calcarea	26	7.83	7.24	8.30	0.010	0.007	7
Pohlia wahlenbergii	5	8.14	8.01	8.35	0.011	0.006	8
Scorpidium cossonii	13	7.58	7.29	7.98	0.015	0.008	5
Scorpidium scorpioides	7	7.44	7.04	7.98	0.018	0.020	5
Seligeria oelandica	9	8.27	8.15	8.38	0.008	0.003	8
Seligeria patula	6	8.24	8.13	8.35	0.007	0.002	8
Tomentyphum nitens	1	7.39	-	-	0.007	-	6

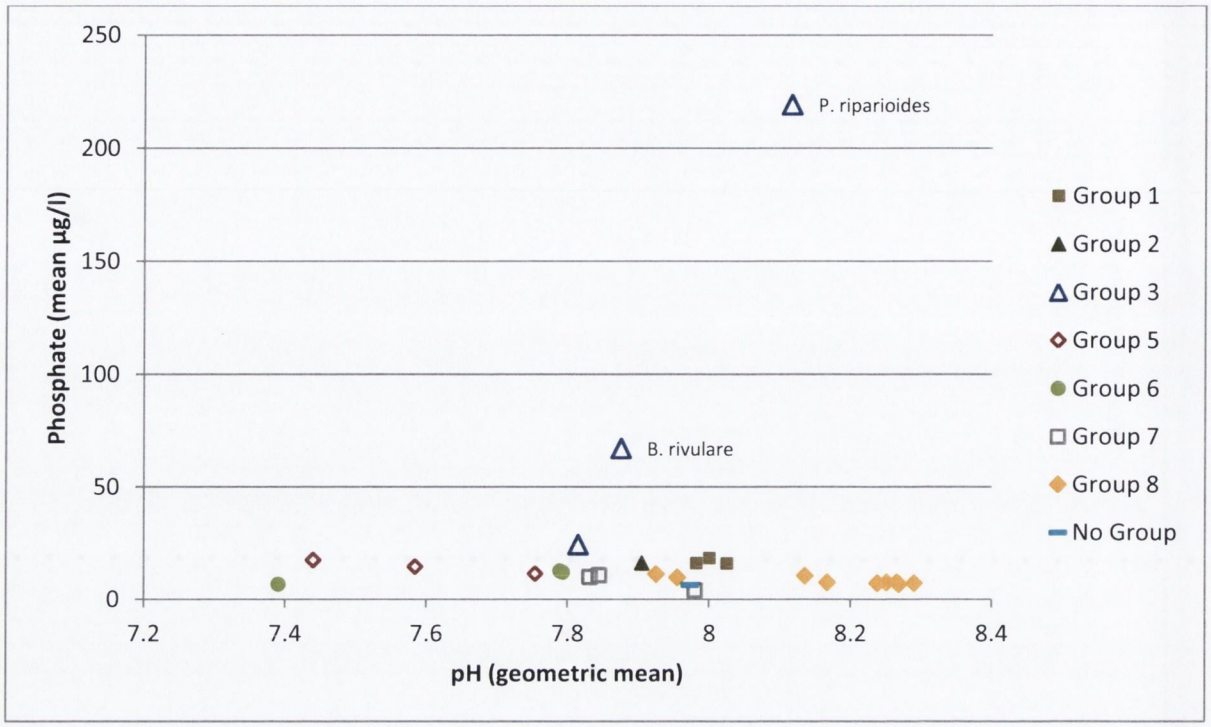


Fig. 5.16: mean pH and phosphate levels for selected bryophyte species over full range of phosphate concentrations. (Species below 50µg/l are as per Fig. 5:15.)

Table 5.13: pH and phosphate values for Group 3 species *P. riparioides* and *B. rivulare*.

Species	n	pH			Phosphate µg/l		
		Geomean	Min	Max	Mean	SD	Median
Brachythecium rivulare	24	7.88	7.00	8.30	67	198	20
Platyhypnidium riparioides	6	8.12	7.82	8.34	219	381	75

Low phosphate availability has been identified as the limiting factor controlling productivity and maintaining species-richness in small sedge communities in other studies (*e.g.* Jeffrey & Pigott 1973, Boyer & Wheeler 1989). In the present study, there is a very highly significant inverse relationship between the number of species per relevé and the spring water phosphate concentration (Fig. 5.17, Spearman's rank correlation r_s = -0.321 ***). Nitrate levels are also very highly significant in this respect in the present study (Spearman's rho = -0.398 ***). Higher nitrate levels are associated with increased cover by *Palustriella commutata* (Spearman's rank correlation r_s = 0.290 **) but no significant linear relationship was found between phosphate levels and cover by *P. commutata.* This species had maximum cover between 10 and 20 µg/l phosphate; all but one of the samples in which it covered at least 50% of the ground surface was within this range for phosphates (n=18). It was present at low cover values below 10 µg/l phosphate (mean cover 12.9%, n=34) and at very low cover values above approximately 50 µg/l PO_4 (Fig. 5.17).

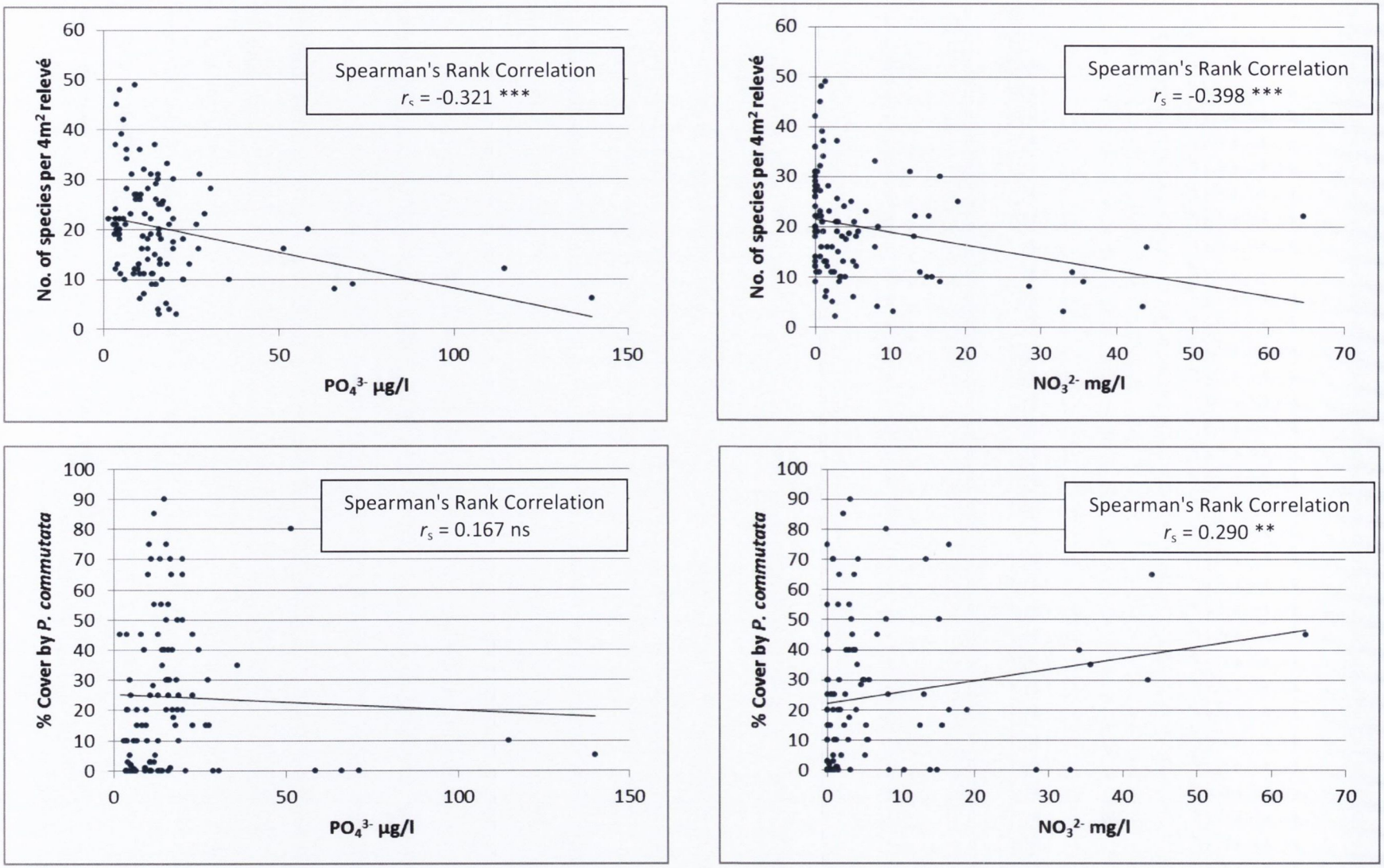


Fig. 5.17: Relationships of macronutrient levels to number of species per relevé and cover by *Palustriella commutata*.

pH and nutrient levels for other species

Mean pH and phosphate levels are plotted in Fig. 5.18 for other species which are ecologically distinctive and/or frequently occurring. In the central part of the graph are the three most frequently recorded sedge species, *Carex flacca, C. lepidocarpa* and *C. panicea*, with mean pH values of 7.77 – 7.88 and mean phosphate concentrations of 12 µg/l. Each of these species is widely dispersed across the full range of both pH and phosphate levels shown in Fig. 5.18. Other sedge species – *Schoenus nigricans, Carex nigra, C. dioica, Eleocharis quinqueflora, Eriophorum angustifolium, E. latifolium* and *C. remota* – have somewhat more limited ranges and the individual values for samples containing these species are shown in Fig. 5.19.

S. nigricans is most frequent at the lower end of the pH range and with very low phosphate levels (Fig. 5.19a); where it was recorded at higher pH levels, phosphate levels were very low and conversely, where it occurred at somewhat higher phosphate levels, it was in low-pH sites. (Proctor (2008) discusses the relevance of anions in the distribution of *Schoenus* in lower pH waters in Ireland, but his water samples are mostly less than pH 7.0 and phosphate levels were not measured in his study.)

The distributions of *Eriophorum angustifolium* and *E. latifolium* are shown in Fig. 5.19b. Apart from its presence in petrifying spring habitats, *E. angustifolium* has a very wide pH range, commonly occurring on wet acid peat and more rarely in calcareous fens (Phillips 1954, Jermy *et al.* 2007); its presence in my samples represents the upper end of a much broader pH spectrum. *E. latifolium*, in contrast, is characteristic of calcareous mires (Jermy *et al.* 2007). However, Fig. 5.19b shows that, within the range of my samples, *E. angustifolium* (n=19, pH 7.04 – 8.38) extends to much higher pH values than *E. latifolium* (n=4, pH 7.29 – 7.79). The larger sample size for the former species may in part explain the wider range, but *E. latifolium* is a much less common species in Ireland than *E. angustifolium* (Jermy *et al.* 2007, Parnell & Curtis 2012), probably due to more exacting habitat requirements including a narrower pH tolerance.

The distributions of *Carex dioica* and *Eleocharis quinqueflora*, which often grow together, are shown in Fig. 5.19c. *E. quinqueflora* is somewhat more common than *C. dioica* in Ireland; both are confined to base-rich fens and flushes and have mostly north-western distributions (Jermy *et al.* 2007, Parnell & Curtis 2012). Within the limits of my samples, both species span a wide pH range: *E. quinqueflora* occurs from pH 7.04 to 8.25 and *C. dioica* from pH 7.31 to 8.38. *Carex dioica* is confined to a narrow range of phosphate concentrations (9 – 31 µg/l), compared to *Eleocharis quinqueflora* (2 – 59 µg/l).

In most cases, *Carex nigra* occurred in the lower part of the pH range of my samples (Fig. 5.19d), with a maximum pH value of 7.98; most samples were in the range 7.44 – 7.57. This species is generally regarded to be indicative of less base-rich conditions than the other *Carex* species in Fig. 5.18 (except for *C. rostrata*); for example, it has a lower Ellenberg value for pH than the other species (Hill *et al.* 1999) and extends onto soils of lower pH value (Grime *et al.* 2007). My data confirm that this pattern holds true within Irish petrifying spring habitats and its presence in my samples marks the upper limits of its pH range.

Carex remota, however, which occurs at the upper end of the pH range in my samples (Fig. 5.19d), has a broad ecological range across habitats other than petrifying springs and the high pH values in my data are atypical for the range of this species (*e.g.* Jermy *et al.* 2007, Hill *et al.* 1999, Grime *et al.* 2007). They arise due to its presence at several woodlands flushed with high-pH water (Glenasmole, Co. Dublin; Knocksink Woods, Ballyman Glen and Knockree, Co. Wicklow; Moneyduff, Co. Leitrim; and in the Camcor River valley, Slieve Bloom Mountains, Co. Offaly), but the species is not confined to this habitat, occurring especially in woodlands that are somewhat less calcareous. It is a diagnostic species of the *Carici remotae-Fraxinetum*; mean pH for this community is 5.64 (n=29; Kelly & Iremonger 1997). It is, however, absent from the lower pH communities recorded during the present study, which are unwooded. Thus, the distribution shown in Fig. 5.19d illustrates its capacity to tolerate very high pH levels but does not indicate a preference for such conditions.

Returning to Fig. 5.18, a cluster of rich-fen forbs and pteridophytes occupies the central part of the graph: *Parnassia palustris, Pinguicula vulgaris, Anagallis tenella, Equisetum variegatum* and *Selaginella selaginoides* (mean pH 7.76 – 7.97 and mean phosphate 8 – 10 µg/l). These correspond in pH and phosphate levels to the rich-fen bryophyte species at the centre of Fig. 5.15. *Samolus valerandi*, although often found on the coast, also occurs in inland sedge-dominated communities such as at Louisa Bridge, Co. Kildare, and in springs in the Burren. *Saxifraga aizoides* occurs at higher pH (but comparable phosphate levels) to the central cluster of rich-fen species (mean pH 8.22 and mean phosphate 11 µg/l, n=11).

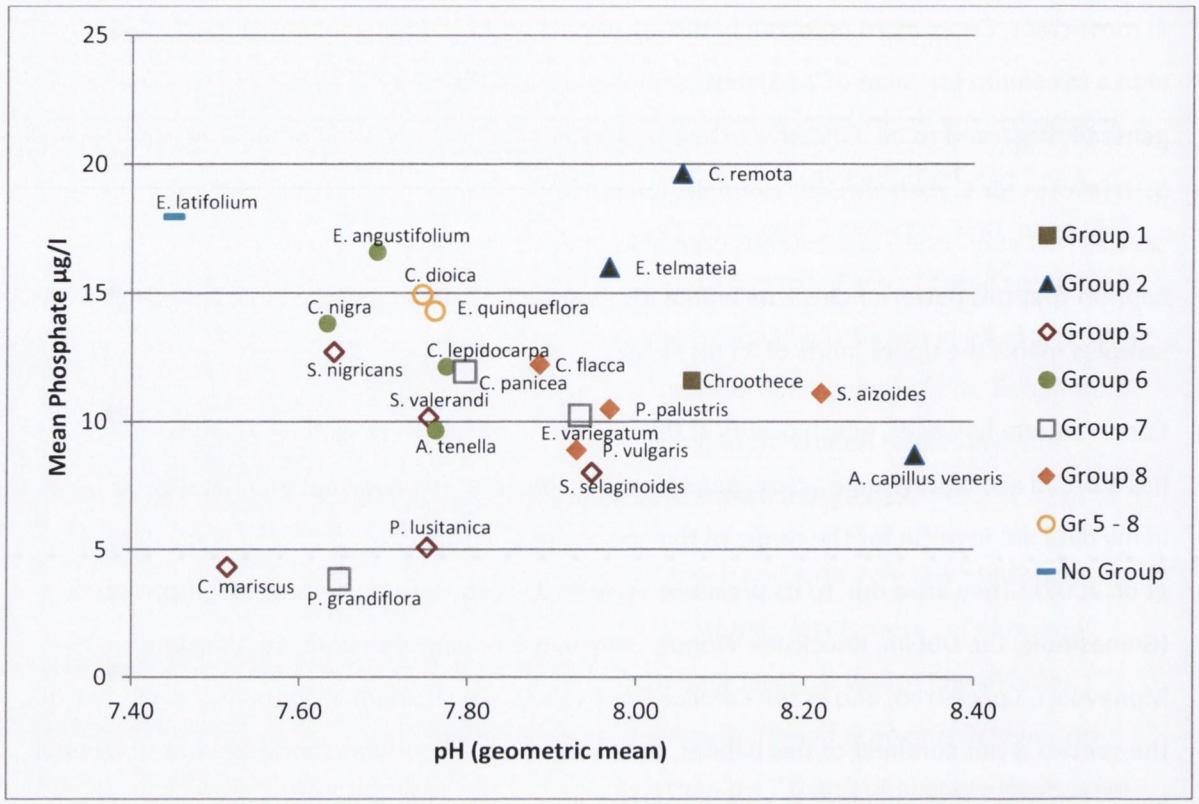


Fig. 5.18: mean pH and phosphate levels for selected vascular plants (and the red alga *Chroothece* sp.).

Table 5.14: pH and phosphate levels for species shown in Fig. 5.18.

Species	pH			Phosphate µg/l		Group	n
	Mean	Min.	Max.	Mean	SD		
Adiantum capillus-veneris	8.33	-	-	9	-	2	1
Anagallis tenella	7.76	7.29	8.47	10	7	6	25
Carex dioica	7.75	7.31	8.38	15	6	Gr. 5 - 8	9
Carex flacca	7.88	7.00	8.38	12	7	8	64
Carex lepidocarpa	7.77	7.04	8.38	12	10	6	46
Carex nigra	7.63	7.44	7.98	14	10	6	7
Carex panicea	7.80	7.04	8.38	12	10	7	45
Carex remota	8.05	7.85	8.25	20	12	2	12
Chroothece sp.	8.07	7.92	8.14	12	6	1	3
Cladium mariscus	7.51	7.40	7.63	4	0	5	2
Eleocharis quinqueflora	7.76	7.04	8.25	14	14	Gr. 5 - 8	16
Equisetum telmateia	7.97	7.13	8.38	16	6	2	17
Equisetum variegatum	7.93	7.73	8.30	10	3	7	3
Eriophorum angustifolium	7.69	7.04	8.38	17	12	6	19
Eriophorum latifolium	7.45	7.29	7.79	18	13	No Group	4
Parnassia palustris	7.97	7.39	8.38	10	8	8	19
Pinguicula grandiflora	7.65	7.41	8.06	4	0	7	3
Pinguicula lusitanica	7.75	7.40	8.25	5	2	5	6
Pinguicula vulgaris	7.93	7.40	8.38	9	5	8	29
Samolus valerandi	7.75	7.19	8.47	10	7	5	8
Saxifraga aizoides	8.22	7.86	8.38	11	9	8	11
Schoenus nigricans	7.64	7.04	8.47	13	12	5	24
Selaginella selaginoides	7.95	7.51	8.38	8	5	5	18

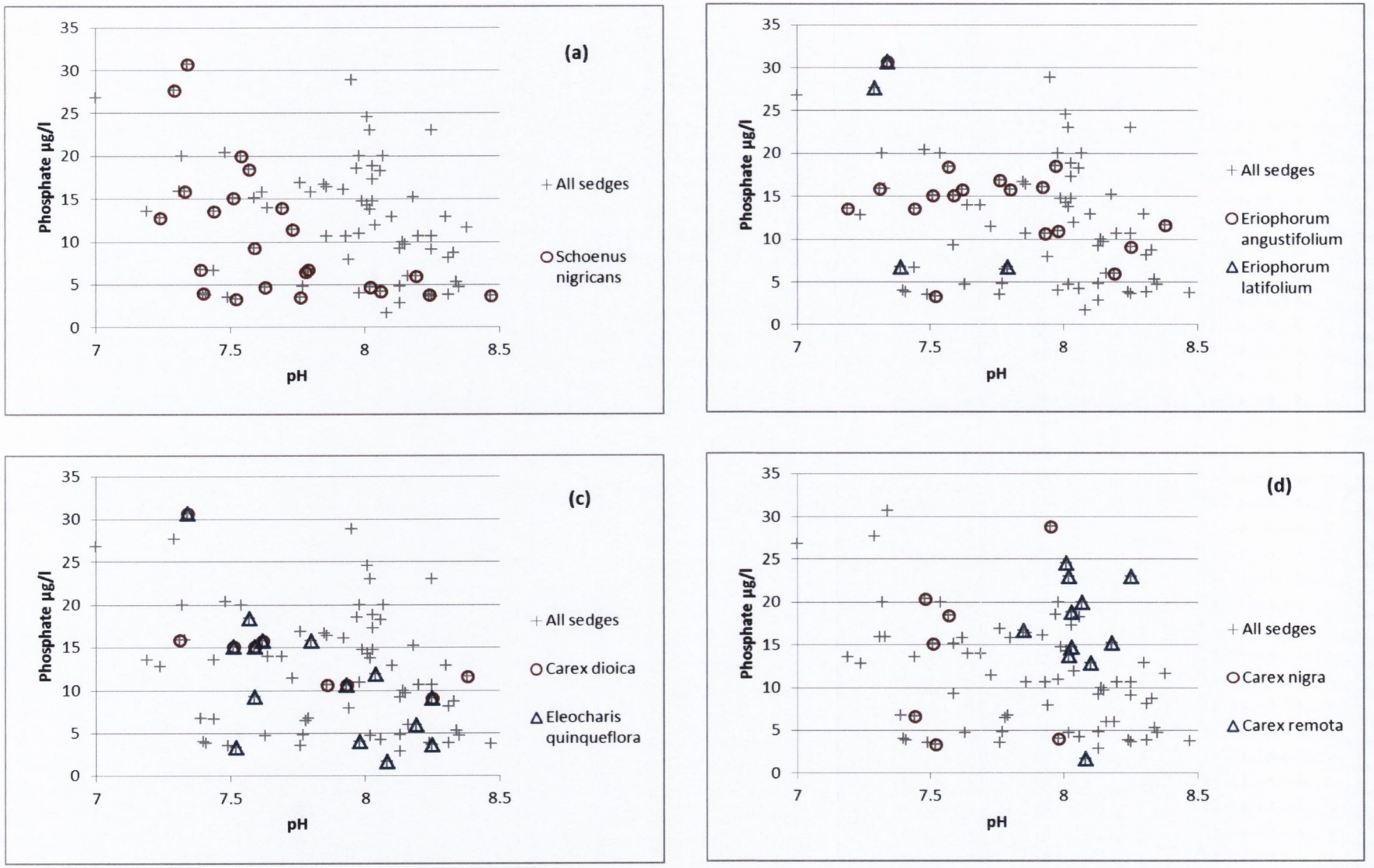


Fig. 5.19: pH and phosphate levels for selected sedge species

Pinguicula grandiflora and *P. lusitanica* occur at very low phosphate levels (and relatively low pH values) with means of 4 and 5 µg/l phosphate and pH 7.65 and 7.75 respectively. Thus, *Pinguicula* species in my samples occur in the order *P. vulgaris, P. lusitanica* and *P. grandiflora* along decreasing gradients of pH and phosphate. The 'typical maximum' value for water pH for *P. vulgaris* in fens in the UK is 7.08, and the 'extreme maximum' is pH 8.22 (Heslop-Harrison 2004); in my samples (n=29), it grows in waters from pH 7.40 to 8.38 (median pH 7.98). UK data for *P. lusitanica* also show that it occurs at lower pH values than *P. vulgaris*, in the range pH 4.5 to 7.1 and with a mean pH of 5.7 (n=39, Heslop-Harrison 2004). In my samples (n=6), the pH range is 7.40 to 8.25 with a median pH of 7.64. Thus, pH values in my samples are very much higher than the typical values reported for these species. (Heslop-Harrison did not provide water pH values for *P. grandiflora*.)

The red alga *Chroothece* sp. occurred in spring water with similar phosphate levels to that of the rich-fen species (mean 0.012 µg/l phosphate). Its slightly higher mean pH value of 8.07 may reflect its coastal location (pH range 7.92 – 8.14). Pentecost *et al.* (2013) reported pH values from four *Chroothece* sp. sites in Britain, ranging from7.21 to 8.48, with a geometric mean of 8.00.

Adiantum capillus-veneris, for which I had only a single sample, grew in spring water with high pH (pH 8.33) and low phosphate levels (9 µg/l phosphate).

Cladium mariscus occurred at low mean phosphate concentration (4 µg/l) and at low pH (mean pH 7.51); these water samples were collected in north-west Mayo. It occupies a similar location on Fig. 5.18 to that of *Tomentypnum nitens* on Fig. 5. 15. *T. nitens* has several stations around Bellacorrick, not far from where the *C. mariscus* water samples were collected (Lockhart *et al.* 2012), although it was not found at these locations during the present survey. The *T. nitens* water sample was collected at Pollardstown Fen, where *C. mariscus* is abundant.

The predominantly woodland species *Equisetum telmateia*, (mean pH 7.97, mean phosphate 16 µg/l) falls close on the graph to *Carex remota* with which it often grows.

Rare species

Saxifraga aizoides was growing at 11 water sampling locations: six on the Benbulbin Range, two on nearby Arroo Mountain, Co. Leitrim, two in west Fermanagh and one at Murlough Bay, Co. Antrim (Table 5.15 below). The Benbulbin and Fermanagh *S. aizoides* relevés all belong to Group 8 *S. aizoides-S. oelandica* Springs and all have similar water composition, with the high pH values and low concentrations of solutes that are characteristic of that group. The Fermanagh samples contain slightly lower concentrations of some ions than the Benbulbin samples. (One Fermanagh

sample also had a lower pH of 7.86 compared to the consistently high values recorded on Benbulbin.) The Arroo Mountain water samples, however, contain higher levels of solutes than the Benbulbin samples; they contain much higher concentrations of sulphates and potassium and are slightly higher in magnesium, sodium and alkalinity. The relevés from Arroo Mountain containing *S. aizoides* (QL202, QL203) were assigned to Groups 4 and 7 (by fuzzy cluster analysis of vegetation, independently of water composition). The Murlough Bay site at which *Saxifraga aizoides* occurs differs in water composition to both the Benbulbin Range and Arroo Mountain; it has much higher alkalinity and contains more calcium, it has higher nutrient levels (both nitrates and phosphates) and is slightly higher in sodium and chloride (it is closer to the coast than the other locations, but not within the spray zone).

Seligeria oelandica grows alongside *S. aizoides* at the Benbulbin Range sites, in west Fermanagh and on Arroo Mountain, thus tolerating concentrations of potassium and sulphate that are higher than at the Benbulbin Range sites. It does not, however, occur at Murlough Bay. This location is outside the geographical range of *S. oelandica* which, in Ireland, is confined to the Benbulbin Range, Arroo Mountain and west Fermanagh. However, the Irish populations of *S. aizoides* are also confined to the north-west of Ireland, in Counties Sligo, Leitrim and Fermanagh, apart from this single station at Murlough Bay. The microtopography of springs at the two locations is somewhat different; at Murlough Bay the soil is deeper and less stony, lacking the flushed rocks surfaces on which *S. oelandica* typically grows, but the difference in water composition, with much higher alkalinity, calcium and nutrient concentrations, may also serve to exclude *S. oelandica* from this region.

Hymenostylium recurvirostrum var. *insigne* grows with *S. aizoides* and *S. oelandica* on the Benbulbin Range. It also occurs on Arroo Mountain in close association with these two species (it was not recorded there during the present survey, but it was found by David Holyoak in 2000, c. 400m east along the same cliff-face from which the water sample was collected, growing with *S. aizoides*, *S. oelandica* and *Orthothecium rufescens*). It is not known from Fermanagh, despite the similar chemistry of spring water, or from any other locations in Ireland apart from the Benbulbin Range and Arroo Mt (Lockhart *et al.* 2012).

Orthothecium rufescens, likewise, occurs at the same locations on the Benbulbin Range and Arroo Mountain. It has also been recorded in Fermanagh and Donegal, but not during the present survey. Outside of the north-west of Ireland, its only station is in the Burren. Water composition at this Burren location (QL090, WS043) is remarkably similar to the Benbulbin spring water samples with high pH and low solute concentrations. The Burren sample is slightly lower in magnesium, phosphate and sulphate concentrations than the Benbulbin samples (Table 5.15).

A caveat applies to water analysis at Murlough Bay. *S. aizoides* was growing on a steep hillside, on damp, laterite soil with no surface water available for collection (Photo 5.13). The water sample was collected from a trickling stream adjoining the colony on one side. The water irrigating the *S. aizoides* colony and that flowing in the stream seemed to be issuing from the same source, but seepage through the laterite soil may have modified the water chemistry somewhat and *S. aizoides* was not growing directly in the stream water. The relevé containing *S. aizoides* was assigned to Group 8 by fuzzy cluster analysis. A separate relevé recorded along the stream from which the water sample was collected was assigned to the very different Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Springs and Flushes. Analysis of the water sample from the latter relevé showed it to be intermediate between data for Group 3 and Group 8.

Table 5.15: Comparison of spring water analysis from five geographical locations showing occurrence of rare species. Concentrations are mg/l except where otherwise stated.

	Benbulbin Range (n=6)			West Fermanagh	Arroo Mountain	Murlough Bay	Burren
	Mean	Min.	Max.	Mean (n=2)	Mean (n=2)	(n=1)	(n=1)
pH	8.26	8.13	8.35	8.00	8.29	8.30	8.31
Alkalinity	162.5	145.7	184.3	143.4	202.4	304.0	182.0
Ca	47.41	34.76	59.34	43.63	55.34	95.71	54.16
Mg	4.96	3.18	7.92	1.68	10.35	3.13	1.66
K	0.35	0.28	0.43	0.32	1.01	0.74	0.43
Na	7.68	6.33	9.56	7.40	10.09	12.50	6.63
Chloride	10.28	7.03	13.38	11.32	12.39	18.86	8.45
Nitrate	0.57	<0.07	1.34	<0.07	0.65	4.08	0.94
Phosphate µg/l	7	5	11	10	11	36	4
Sulphate	4.83	2.75	6.74	1.71	26.46	5.42	1.50
Saxifraga aizoides		✓		✓	✓	✓	
Seligeria oelandica		✓		✓	✓		
Hymenostylium insigne		✓			✓ (DH)		
Orthothecium rufescens		✓			✓ (DH)		✓
Fuzzy Cluster Group		8		8	7 and 4	3 (or 8)[a]	8
Water Samples	WS018, 020, 021, 022, 098, 099			WS093, 094	WS012, 013	WS123	WS043
Relevés	QL129, 133, 135, 136, 196, 197			QL171, 218	QL202, 203	QL208	QL090

[a] See text for explanation

DH = record by D. Holyoak, 2000. Other records (✓) were made during the present study

5.3 Discussion

While there is considerable variation in the chemical composition of the spring waters sampled, all have high pH values and high alkalinity and calcium concentrations compared to most naturally occurring waters, but they are comparable to tufa-forming waters reported from other countries (Pentecost 2005). On the whole, pH and alkalinity levels are slightly high, while calcium, magnesium and potassium concentrations are slightly low in Irish petrifying springs compared to data reported in other studies (Pentecost 1999, Pentecost & Zhaohui 2002, Hájek *et al.* 2002, Keppel *et al.* 2011, Arenas *et al.* 2014). Sodium and chloride levels are very variable, in part due to the coastal influence at many sites, but the highest levels, both in Ireland and elsewhere, are associated with deep artesian (inland) springs (Pentecost 1999, Kuczynska & Bartley 2008, Keppel *et al.* 2011). Nitrate levels in Irish petrifying springs are comparable to levels elsewhere, but phosphate levels are lower and sulphate levels are especially low (*e.g.* Pentecost 2005, Arenas *et al.* 2014). Outlying values coincide with some of the more atypical manifestations of the habitat, in terms of both tufa type and vegetation composition.

Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs have the most distinctive spring water composition, with high pH and very low concentrations of solutes. The rare species *Saxifraga aizoides, Seligeria oelandica, Hymenostylium recurvirostrum* var. *insigne* and *Orthothecium rufescens* are not strictly confined to Group 8 samples, but they are for the most part confined to spring water of similar composition. Benbulbin Range spring waters, those collected at *Saxifraga aizoides* stations in west Fermanagh and the sample from the *Orthothecium rufescens* station in the Burren are remarkably similar in composition. The Arroo Mountain samples suggest that these species tolerate somewhat higher levels of potassium and sulphate than are present on the Benbulbin Range but only *S. aizoides* is present in the higher alkalinity and nutrient levels at Murlough Bay. Fuzzy cluster analysis placed the Arroo Mountain and Murlough Bay relevés in different groups to the Benbulbin Range, west Fermanagh and *O. rufescens* Burren relevés based on vegetation data, in spite of the shared rare species which are highly significant indicator species of Group 8. Separating the relevés in this way coincides with differences in water composition and confirms that the fuzzy cluster classification presented in Chapter 3 reflects the broader ecological conditions, not just the floristic data on which it was based.

The relationship between pH and alkalinity within petrifying spring habitats is clearly shown to be a negative one (Fig 5.3). Attempts were made to test this pattern within individual springs, by sampling at increasing distance from the springhead, but these were unsuccessful. The chemical composition of spring water changes as it emerges from below ground and comes into contact

with the atmosphere; in particular, pH, alkalinity and calcium levels are subjected to change as water becomes aerated (*e.g.* Emeis *et al.* 1987, Keppel *et al.* 2011, Arenas *et al.* 2014). Some samples were collected immediately upon emergence above ground, where there was a plentiful flow of water at the spring head; others dripped slowly, interacting with the atmosphere and taking several minutes to fill a bottle; still others were siphoned from pools on flat ground where the water had been sitting an indeterminate length of time, during which evaporation could condense the solutes or rain water could dilute them. Even where there was a plentiful flow of water below the spring head, this was nearly always supplemented by additional seepages further downhill, so that the relationship between distance from the springhead and contact time with the atmosphere was not a simple one. In addition, aeration and degassing of spring water is dependent on turbulence due to flow rate and microtopography (*e.g.* Zhang *et al.* 2001, Chen *et al.* 2004). At some sites it was challenging to collect sufficient water to fill the bottles by any means and at two sites, Thomastown Quarry and Clonaslee Esker, there was no water whatsoever available after the dry summer of 2013. Having been collected in these variable conditions, the samples in this study are not well suited to investigating the chemical changes within sites associated with equilibration of spring water as it makes contact with the atmosphere, and the deposition of tufa. The samples are however, highly relevant to the ecological conditions in which plants are growing, and in all cases were collected as close as possible to the location and hydrogeological conditions of the vegetation records.

pH and alkalinity levels are closely associated with the vegetation and tufa-forming characteristics of the different fuzzy cluster plant communities. Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs and Group 7 *Palustriella falcata-Carex panicea* Springs have high pH levels coupled with low alkalinity (within the ranges of this study). Conversely, Group 5 *Schoenus* Springs and Group 6 *Carex lepidocarpa* Small Sedge Springs are relatively low in pH and high in alkalinity. These four groups are weakly to moderately tufa-forming; they are characterised by paludal tufa or thin stream crust tufa. The most strongly tufa-forming communities, with massive, highly consolidated tufa cascades, have high pH values coupled with moderate to high alkalinity levels; these are Group 1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades, Group 2 *Palustriella commutata-Geranium robertianum* Springheads, Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes and Group 4 *Palustriella commutata-Agrostis stolonifera* Springheads.

The ecological range of *Palustriella commutata* and *P. falcata* is shown by other studies to be much broader than the range reported in this study. Both species can tolerate much lower pH levels than were recorded in the present study, and thus petrifying springs represent the extremes of their range even for these calcicolous species (Bell & Lodge 1963, Hedenäs &

Kooijman 2004). Likewise, species such as *Pinguicula vulgaris* and *P. lusitanica* grow in Irish petrifying spring waters at much higher pH levels than their typical range in other habitats (Heslop-Harrison 2004).

Elevated concentrations of nitrates and phosphates are associated with low species diversity. The three bryophyte species growing in the highest phosphate levels, *Platyhypnidium riparioides, Brachythecium rivulare* and *Cratoneuron filicinum*, are all significant indicator species of Group3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Springs and Flushes. There is conflicting evidence in the literature as regards the ecology of *Platyhypnidium riparioides* in relation to elevated nutrient levels in waters (Ceschin *et al.* 2012), but its presence at Woodlands shows that it has the capacity to thrive at very much higher phosphate concentrations than were recorded for all other bryophyte species apart from B*rachythecium rivulare*. *B. rivulare* has also been found in other studies to be associated with increased phosphate levels (Scarlett & O'Hare 2006). *Cratoneuron filicinum* is associated with higher phosphate levels than *Palustriella commutata* in my samples, confirming Oberdorfer's observation that the former often replaces the latter at eutrophic sites (Oberdorfer 1977).

The results of the pilot investigation of phosphate levels found that all phosphorus was present as soluble reactive phosphorus (SRP) and total phosphorus analysis was therefore not carried out for the main data set. Phosphate measurements are often omitted from water analysis, (*e.g.* Arenas *et al.* 2014, Auqué *et al.* 2014, Vázquez-Urbez *et al.* 2010, Keppel *et al.* 2011, Proctor 2008). Boyer and Wheeler's (1989) study of Short-Fens using SRP analysis found similar levels to the present study; it is unclear what method was used by Hájek *et al.* (2002) in the W. Carpathians where higher phosphate levels were reported. It is possible that phosphate levels were underestimated in the present study, but to measure total phosphorus within the present study would have required a much smaller sample size (for all chemical parameters).

Sampling different sites in different years was not ideal due to variations in weather patterns. Water levels were particularly low in September 2013, to the point where it was impossible to collect water at two sites; this could have caused concentration of solutes in samples. However, no statistical difference could be found between the two years, based on ten chemical parameters of nine samples collected in both years. The logistics of sampling a large number of widely dispersed, often remote sites, and returning to the laboratory promptly to carry out analysis, made it impossible to carry out all sampling in one month. The alternative option of collecting in two consecutive months in the same year was considered equally or more prone to fluctuations in weather due to seasonal factors.

Within the range of spring waters sampled, the NMS joint plots and Spearman rank correlations show that chemical variables are less strongly correlated with the ordination axes than other abiotic variables, such as tufa type, slope and shading. My samples represent a narrow range of habitats, within which chemical composition of water is relatively homogenous; in a broader habitat context, water chemistry is of much greater importance, as tufa formation can only take place within a relatively limited set of chemical conditions.



Photo 5.1: Tufa cascade with pH11.38 at Spanish Point (WS032), Co. Clare, April 2012. The surface is almost entirely devoid of plants, except along the uppermost margin; filamentous green algae cover the lower portion.



Photo 5.2: Detail of tufa at Spanish Point (WS032) with an unusual 'honeycomb' pattern not seen elsewhere during the present study. April 2012.



Photo 5.3: Tufa cascade, covered by *Didymodon tophaceus*, below a pipe outfall on the coast near Skerries, Co. Dublin (WS048, QL155). The bar mounted across the cascade was used to measure the tufa deposition rate (TB15, mean rate 11.6mm/yr; see Chapter 7 for details). March 2011.



Photo 5.4: View from above the location of WS048 and QL155, with water discharging from pipe. This water sample has had the highest concentration of potassium, 22.97mg/l. May 2013.



Photo 5.5: Steam rising from the Spa Well at Louisa Bridge, Co. Kildare, on a cold winter's day (Dec. 2012). This warm spring (*c*.16°C) has high levels of sodium and chloride; it is not tufa forming.



Photo 5.6: Tufa-depositing pools and paludal habitats at Louisa Bridge fed by the combined water sources of the Spa Well and cold, alkaline springs (June 2012).



Photo 5.7: Iron-rich, tufa-forming spring at Ballyman Glen (WS066) containing 7.14 mg/l iron (May 2012). The vegetation is dominated by *Equisetum telmateia*.



Photo 5.8: Fen vegetation, dominated by *Molinia caerulea, Juncus articulatus, Carex lepidocarpa, Eleocharis quinqueflora, Palustriella commutata* and *Campylium stellatum* at Ballyman Glen (QL120, August 2012). Nitrate concentration in the water is high, at 64.70 mg/l (WS067).



Photo 5.9: Lake in golf course on north side of the R. Liffey near Palmerstown, Co. Dublin, May 2013.



Photo 5.10: Overflow from lake (above) with large tufa cascade, dominated by *Platyhypnidium riparioides* and *Brachythecium rivulare* (May 2013). Water phosphate levels are very high, at 991 µg/l. Discarded brushwood lies to the left of the cascade (Section 6.1.4).



Photo 5.11: A pipe discharges surface drainage water into a small stream close to the River Liffey near Palmerstown, Co. Dublin, May 2013. WS137 and WS138 were collected downstream and contain elevated sulphate levels (146.88 and 142.22 mg/l respectively).



Photo 5.12: Below the pipe outfall, the stream is visibly polluted with cloudy blue-grey water (May 2013). The derelict remains of a sluice and water storage tank can be seen (a mill race is located between the stream and the R. Liffey).



Photo 5.13: Murlough Bay, Co. Antrim, July 2013. Two relevés (indicated by arrows) were recorded. The uppermost relevé (QL208) contained *Saxifraga aizoides* and was assigned to Group 8. The lower one (QL209) is on a small rivulet of water flowing downhill to one side of the *S. aizoides* colony. It was dominated by *Agrostis stolonifera, Palustriella commutata, Cratoneuron filicinum* and *Brachythecium rivulare* and was assigned to Group 3. A water sample was collected from this rivulet. The upper relevé was on damp ground but without any surface water to collect.

6. Habitat Management

6.0 Introduction

During the course of site visits, land management issues which impacted negatively on the conservation status of petrifying springs were recorded. These observations form the basis for this chapter, along with data from water analysis (Chapter 5). Land use in the areas surrounding springs was noted during site visits and it was also examined on aerial photographs (www.osi.ie and www.googlemaps.ie) up to a distance of approximately 1km. Landowners were not formally interviewed although, at some locations, opportunities arose to discuss issues related to petrifying spring habitats on an informal basis.

There are numerous issues related to anthropogenic influences and the management of petrifying spring sites and their catchments that can impact on their plant communities and conservation status (*e.g.* Pentecost 2005, Cantonati *et al.* 2006, Foss 2007a, Curtis *et al.* 2009). The floristic composition of wetland communities is highly dependent on water pH and nutrient status, as well as the quantity of water, in terms of its flow rate or constancy of flow (*e.g.* Wheeler 1988, Ó Críodáin & Doyle 1994, Fojt & Harding 1995, Wheeler & Proctor 2000, Rozbrojová & Hájek 2008). Eutrophication of the marshland surrounding the karstic lakes of Plitvice National Park, Croatia, for example, has caused changes to the composition of wetland communities and is threatening the conservation status of the tufa-forming habitats (Stančić *et al.* 2010). Some spring and flush communities are dependent on grazing for their continuance (*e.g.* Pigott 1956, McVean & Ratcliffe 1962, Birks 1973, Rodwell 1998b). Loss of such habitats has arisen by the abandonment of marginal lands that are no longer considered profitable to stock with animals and once lost, these habitats are not easily re-established (*e.g.* Gibson *et al.* 1987, Wheeler 1988, Gibson & Brown 1991, Fojt & Harding 1995, Mortimer *et al.* 1998). Other issues include physical damage, for example, due to nearby construction works, pressures associated with recreational activities and the impact of alien species. At some of the larger petrifying spring sites outside Ireland, multiple damaging impacts have been identified. Intense visitor pressure at Pamukkale, Turkey, for example, has given rise to problems associated with visitors swimming in tufa-rimmed pools, inadequate provision of sewage treatment facilities, mechanical damage from visitors walking over the travertine surface and vibrations, gas emissions and dust from vehicles arriving in nearby car parks (Dilsiz 2002; see Photos 6.44 to 6.47).

This chapter looks firstly at issues related to nutrient enrichment and pollution of spring water. Problems associated with changing the pattern of flow are then discussed, followed by matters

related to grazing of lands in which petrifying springs are located, physical damage to the habitat, the impact of recreational activities and the occurrence of non-native species. Some examples of tufa formation in modified environments are also considered here, as are natural processes of change. Area estimates given in this chapter are the approximate area impacted by the springs at which relevés were recorded. These data are provided to give a general indication of the extent and relative importance of the various issues encountered; they were **not** collected by random sampling techniques and they **cannot** be considered an accurate statistical representation of Irish petrifying spring habitats as a whole.

6.1 Habitat Management Issues

6.1.1 Alterations to chemical composition of groundwater

Nutrient Enrichment: Nitrates

Levels of nitrate in excess of 10 mg/l NO_3^- are regarded by the Environmental Protection Agency to be indicative of anthropogenic inputs (McGarrigle *et al.* 2010). Nitrate concentrations in 19 of my samples (17%), from 13 separate sites, were in excess of 10 mg/l (Table 6.1). The highest nitrate concentration was recorded in a water sample from Ballyman Glen, Co. Wicklow (WS067, 64.70 mg/l at QL120, Photo 5.8). This is a species-rich site of high conservation value and the flora is not indicative of high levels of nutrient enrichment. It includes species such as *Anagallis tenella, Parnassia palustris* and *Palustriella falcata*, all of which are characteristic of nutrient-poor habitats (for example, Figs 5.10 to 5.12, 5.12, 5.18). The site is adjoined by disused landfill sites (now capped) and by arable land and pasture.

Table 6.1: Nitrate levels in water samples

Nitrate concentration	No. of water samples	% water samples
< 10 mg/l NO_3^-	96	83.5%
10 – 30 mg/l NO_3^-	13	11.3%
>30 mg/l NO_3^-	6	5.2%
Total	**115**	**100%**

Next highest, were five samples ranging from 32.99 – 44.05 mg/l, collected at separate coastal springs: two springs between Skerries and Balbriggan, Co. Dublin (WS047 at QL153 and WS048 at QL155); one at Ardmore Pt, Co. Wicklow (WS081 at QL216) and two at Rathcor, Co. Louth (WS128 at QL213 and WS129 at QL214, Photos 6.1 and 6.2, see also Photos 3.20 and 5.3). At each location, the hinterland was used for intensive crop production (Photos 6.3 and 6.4) and golf courses were situated close to the springs at Skerries and Ardmore Point. The spring sites all contained massive tufa cascades; the rate of tufa deposition was measured at two of these cascades, near Skerries, and one was found to have the fastest mean rate of tufa deposition compared with 11 other Irish locations at which measurements were made (Photo 3.20 and Photos 7.3 to 7.6, TB14, Chapter 7). Six relevés were recorded in total at these three coastal locations. On average they contained only 7.8 species per $4m^2$ relevé. The constant species were *Palustriella commutata, Eucladium verticillatum, Didymodon tophaceus, Festuca rubra* and *Agrostis stolonifera*, while *Plantago maritima, Tussilago farfara, Taraxacum officinale* agg., *Carex flacca, Juncus articulatus* and *Cratoneuron filicinum* were occasional.

Nitrate levels of 10 – 30 mg/l were recorded in thirteen samples (11.3% of water samples). Three were collected on the coast (Spanish Point, Co. Clare; Ballincar, Co. Sligo and Balscadden Beach on Howth Head, Co. Dublin). Nine were from inland locations (Pollardstown Fen, Hartwell and Seven Springs, Co. Kildare; Broadboyne Bridge, Co. Meath and Knockree, Co. Wicklow). All locations are adjoined by a combination of pasture and arable land, along with rural housing. There are golf courses near the springs at Spanish Point, Balscadden and Seven Springs and conifer plantations close to the springs at Knockree. Arthurstown Landfill (now closed) is located close to the springs at Hartwell.

Nutrient Enrichment: Phosphates

In the case of phosphate, the Environmental Quality Standard (EQS) set under the Water Framework Directive is 107 µg/l PO_4^{3-} (0.035mg/l P), although EPA monitoring in the period 2007 to 2009 found that phosphate levels in samples collected from Irish groundwaters (n=211) were mostly below 15µg/l (McGarrigle *et al.* 2010). Three of my water samples exceeded the EQS for phosphate (Table 6.2 below). The highest phosphate concentration, WS139 with 991 µg/l, was collected from the overflow of a pond in a golf course close to the River Liffey, Co. Dublin (Photos 5.9 and 5.10). The corresponding relevé contained only two species, *Platyhypnidium riparioides* and *Brachythecium rivulare*. The next two highest concentrations were from samples collected nearby on the opposite side of Liffey (WS137 and WS138, both with >100 µg/l phosphate, discussed below). Six additional samples contained in excess of 30 µg/l phosphate, although they were within the EQS (<107 µg/l): one from Broadboyne Bridge (also with elevated nitrate, above),

one from Ardmore Point, Co. Wicklow (from a separate spring to the high nitrate sample, above), two from Lisduff Fen, Co. Offaly, one from Knocksink Wood, Co. Wicklow and one from Murlough Bay, Co. Antrim. The adjoining fields at these sites consist of both arable and pasture land. The most frequently occurring species in the relevés from the locations of these nine samples were *Agrostis stolonifera, Brachythecium rivulare, Palustriella commutata, Cratoneuron filicinum* and *Platyhypnidium riparioides* and the mean number of species per $4m^2$ relevé was 12.3. Forty further water samples were in the range 15 – 30 µg/l PO_4^{3-}.

Table 6.2: Phosphate levels in water samples

Phosphate concentration	No. of water samples	% water samples
<15 µg/l PO_4^{3-}	66	57.4%
15 - 30 µg/l PO_4^{3-}	40	34.8%
30 – 107 µg/l PO_4^{3-} (< EQS)	6	5.2%
> 107 µg/l PO_4^{3-} (> EQS)	3	2.6%
Total	**115**	**100%**

EQS: Environmental Quality Standard

Of the sites with more than 30 µg/l PO_4^{3-}, the three Liffey valley sample locations, and Knocksink Wood and Broadboyne Bridge contain tufa cascades or tufa dams (Photos 6.5 to 6.8, also Photo 3.16). At the Liffey valley locations and in Knocksink Wood, the tufa deposits are inundated with constantly flowing shallow water, and they are shaded by nearby trees; all are coated with filamentous algae, dark green (almost black) in colour. The cascade at Broadboyne Bridge is the only site at which both phosphates exceeded 30 µg/l and nitrates exceeded 20 mg/l. Dark green filamentous algae were conspicuous in shady, wet parts. Drier, less shaded areas were dominated by *Cratoneuron filicinum*.

The vegetation on the tufa cascade at Hartwell (nitrate 14.0 mg/l, phosphate 18 µg/l) was unlike that of any other cascade (Photos 6.9 to 6.12). It was dominated in places by species indicative of mesotrophic to eutrophic conditions, including *Petasites hybridus, Scrophularia auriculata, Urtica dioica, Epilobium hirsutum, Ranunculus repens, Holcus lanatus* and *Dactylis glomerata* (Ellenberg values 5-8 for fertility, Hill *et al.* 1999). More characteristic petrifying spring species were present locally, including *Palustriella commutata, Cratoneuron filicinum, Brachythecium rivulare* and *Pellia endiviifolia*. *Apium nodiflorum* and *Nasturtium officinale* agg. were abundant in fast flowing rivulets and colonies of *Vaucheria* spp were present along parts of the steep edge of the tufa cascade. The cascade was partly shaded by nearby trees. Water was collected from two separate locations on the cascade in both September 2012 and 2013. The mean phosphate

concentration was 20 µg/l and that of nitrate was 14.49 mg/l. Thus, both are slightly elevated above typical background levels. Calcium and alkalinity levels are very high in these samples, with mean values of 124.65 and 394.1 mg/l respectively. Thus, the atypical species found on this tufa cascade can tolerate the extreme calcium and alkalinity levels, and can come to dominate the vegetation even at only moderate inputs of nutrients.

Other Pollutants

Two water samples collected nearby in the River Liffey valley, Co. Dublin, had very high levels of sulphates: 142.22 and 146.88mg/l (WS138 and WS139, Photos 6.13 to 6.15; also 3.16, 5.11 and 5.12). They were collected in a stream on the south side of the Liffey, a short distance before it joins that river near Wren's Nest weir. These samples also had elevated phosphate levels in excess of the EQS (115 and 140 µg/l). A large pipe feeds into the top of the stream and additional seepages occur along the banks. One water sample was collected immediately below a seepage area and the other was taken further downstream in the water containing both seepage and pipe flow; the sample collected at the seepage zone unexpectedly contained (slightly) higher levels of both sulphate and phosphate. This stream flows over a series of tufa dams and, at one time, there were substantial deposits along some tens of metres of its course. Now, however, the tufa is being eroded as the river channel cuts through the dams, in spite of high calcium concentrations in the water (mean 145.14 mg/l calcium). The tufa is black in colour instead of the characteristic light beige colour and there are few plant species growing on it. The water is visibly discoloured and the stream banks are strewn with plastic debris. The N4 and M50 roads, as well as a major retail development and a golf course are located nearby.

Two relevés were recorded, one at the seepage zone and one on dams a short distance downstream. *Platyhypnidium riparioides* was the most abundant species (40% cover at the seepage), along with smaller amounts (max. 10% cover) of *Palustriella commutata* and *Cratoneuron filicinum*. There were small amounts (up to 2% cover) of *Hedera helix, Chrysosplenium oppositifolium, Ficaria verna, Cardamine flexuosa, Geranium robertianum, Veronica montana, Agrostis stolonifera, Brachythecium rivulare, Plagiomnium rostratum* and *Conocephalum conicum* s.s.

6.1.2 Removing or altering the flow of water

Negative impacts associated with altering the flow of water relate to diverting the course of water before it reaches the springhead and extracting water from spring-associated wetlands for usage elsewhere.

Measures to control the flow of water before it reached the spring head were noted in close proximity to 5 relevés (3%, Table 6.3 below). Several coastal sites were characterised by the presence of massive tufa cascades but another ecologically important coastal petrifying spring habitat consisted of more diffuse seepage zones where the water issued over large areas of gently sloping ground giving rise to thinner paludal tufa deposits, for example at Rathcor (Photos 6.2 and 6.17). However, at three coastal locations - Balscadden and Redrock on Howth Head, and near Skerries, Co. Dublin (Photos 5.3, 5.4 and 6.18) - tufa-forming water issued onto the beach via a pipe into which surface water from the land above had been channelled. The result of channelling the water is that it can only impact on a much smaller area; while the water is still often tufa-depositing below the pipe outfall, the habitat is very much reduced in extent and depleted of species. For example, QL155, near Skerries, was recorded below a pipe outfall; tufa is accumulating here at 11.6mm per year on average (TB15 Chapter 7) but the only species recorded were *Didymodon tophaceus, Agrostis stolonifera* and *Cochlearia officinalis* (Photo 5.3). The intermittent nature of discharges from pipes compared to the steady flow from natural springs was observed at a number of sites, for example in the Liffey valley and at Skerries.

The potential for large scale water extraction exists at two sites; Pollardstown Fen contains a system of drains connected to the Grand Canal via the Milltown Feeder (Photo 6.19), and the land around Ballynafagh drains into the same canal via the Blackwood Feeder. These large sites amount to approximately 10% of the total area of petrifying spring habitats surveyed. The usage and management of these feeder systems has the potential to influence water levels over large areas of spring-dependent communities.

Table 6.3: Management issues recorded in or adjacent to relevés

Management Issue	No. of relevés	% relevés	Estimated Area (ha)	% Area	Plant Communities
Water diversion	5	3%	0.09	1%	Gr. 1, 3, 4
Water extraction (small scale)	11	6%	0.45	4%	Gr. 4 - 7
Water extraction (large scale)	8	4%	0.98	10%	Gr. 4 - 7
Undergrazing	21	11%	1.05	10%	Gr. 6 (also 2, 4, 5, 7)
Overgrazing	10	5%	0.78	8%	Gr. 7, 8 (also 4 - 6)
Physical damage	4	2%	0.15	1%	Gr. 4 - 6
Landfill & refuse	24	13%	0.57	6%	Gr. 2, 3, 4, 6, 8
Recreation	17	9%	0.72	7%	Gr. 2 - 6
Non-native species	12	6%	0.55	5%	Gr. 2, 3, 8
Adjacent conifers	18	10%	0.81	8%	Gr. 1 - 6

Small scale water extraction (Photos 6.20 to 6.23) was observed at 11 relevé locations, representing approximately 4% of the area surveyed. In some cases, especially in the Burren, this was for watering livestock via nearby troughs (*e.g.* at Feenagh and Glenamannagh in the Burren, Co. Clare); in other cases it was piped offsite for farmyard or domestic usage (*e.g.* at Corhawnagh, Co. Sligo, Photo 6.20). At most sites, only a small proportion of the water was being abstracted and negative impacts on the spring flora were minimal. Indeed, making water available to livestock a short distance away from the springhead reduces the need for animals to congregate at the spring, thus reducing trampling and fouling in the immediate vicinity of the spring head (Photo 6.21 compared to 6.22). The least damaging arrangements were the simplest, with an above-ground plastic pipe collecting a small proportion of spring water directly from the spring head (Photo 6.21). More elaborate collection techniques, however, were also encountered and these were damaging; for example at one spring in the Burren (near Termon) a concrete structure had been built to impound water and this eliminated the spring habitat almost entirely (Photo 6.23).

6.1.3 Grazing Levels

Springs on level or gently sloping ground are, or have in the past, most often been subject to some grazing by domestic animals. Others are inaccessible due to their location on steeply sloping cliffs.

Cattle grazed the locations of 17% of relevés, representing an area of approximately 3.21ha of petrifying spring habitats (Table 6.4 below). Sheep grazed approximately 1.42ha (13% of relevés) and horses grazed approximately 0.30ha (3% of relevés). At 30% of relevés (approximately 2.75ha), there was no evidence of grazing domestic animals but grazing by large wild herbivores (deer and goats) was either in evidence or considered likely. 34% of relevés were not accessible to large grazing animals, mostly due to their steep location, but in some cases because of fencing.

Table 6.4: Grazers of relevés

Grazer	No. of relevés	% relevés	Estimated Area (ha)	% Area	Plant Communities
Cattle	32	17%	3.21	32%	Gr. 4 – 7
Sheep	24	13%	1.42	14%	Gr. 2 – 8
Horses	5	3%	0.30	3%	Gr. 3, 6 and 7
Wild grazing	56	30%	2.75	27%	All Groups
Other [a]	5	3%	0.19	2%	Group 6
No grazing	64	34%	2.28	22%	All Groups
Total	**186**	**100%**	**10.15**	**100%**	

[a] See Louisa Bridge (below)

Evidence of undergrazing was recorded at 21 relevés (representing c. 1.05ha); it is most frequent and damaging in Group 6 *Carex lepidocarpa* Small Sedge Springs. Scrub encroachment and accumulating leaf litter, suggesting a reduction or cessation of grazing, were observed at Pollardstown Fen (Photo 6.26), Ballynafagh and Ballyman Glen. Robust grasses and rushes, such as *Molinia caerulea, Juncus subnodulosus* and *Phragmites australis* were more abundant in these locations, along with tall broadleaved species including *Eupatorium cannabinum* and *Angelica sylvestris* (see Section 3.2.6a). Pockets of more open, low growing vegetation (in which the above relevés were recorded) occur within taller, less species-rich communities – often along tracks where there is some trampling to keep the more robust species in check. There was no evidence of grazing by domestic animals at these sites, although some grazing by wild animals such as deer is likely. The rare moss *Tomentypnum nitens* occurs locally amongst this dense vegetation at

Pollardstown Fen; shading by tall vegetation is a potential threat to this species (Lockhart *et al.* 2012).

At one site, Louisa Bridge (5 relevés, area 0.19ha, Table 6.3), where grazing had ceased, the local authority had instigated a programme of scrub removal. Here, local residents recalled two or three young cattle (up to a year old) grazing the wetland habitats at Louisa Bridge. The yearlings were sold on annually and replaced by calves. This low level of grazing, by light weight cattle, prevented scrub encroachment but avoided excessive trampling and overgrazing. During the past few decades, these lands have not been grazed, and scrub consisting especially of *Rubus fruticosus, Fraxinus excelsior, Salix cinerea* and *Prunus spinosa* had progressively encroached on species-rich *Carex lepidocarpa* Small Sedge Springs. To maintain the conservation status of these wetlands, a programme of scrub removal was instigated by Kildare Co. Council (Lyons 2009a, b). This involved the manual removal of tree seedlings, saplings and suckers, as well as brambles, digging out the roots with a spade (Photos 6.24 and 6.25). Use of heavy machinery was avoided to minimise damage to the fragile wetland habitats. Manual scrub removal, however, is time consuming; it is most successful if tackled in the early stages of colonisation and it is a continuing process rather than a once-off event. This intervention has, in the case of Louisa Bridge (2.3ha wetland and grassland), been successful, but it is unlikely to be a viable option for larger sites.

Conversely, very closely cropped vegetation was observed at other sites – at Dooaghtry (Photo 6.27) and on parts of the Benbulbin Range – which are grazed by sheep. Here, there is a risk of overgrazing, poaching leading to erosion and lack of regeneration of rare species. Overgrazing was considered a threat to approximately 8% of the spring area surveyed.

6.1.4 Physical damage to habitat

Severe physical damage associated with land drainage was observed at two sites – Seven Springs, Co. Kildare and Knocknagur, Co. Galway – during the timespan of this project (1% of area surveyed). At both, species-rich spring communities were lost and the conservation status of sites was drastically reduced due to the clearing and deepening of drains (Photos 6.28 and 6.29). Prior to drainage, the site at Seven Springs contained tufa deposits with *Pinguicula vulgaris, Anagallis tenella, Palustriella commutata, P. falcata, Campylium stellatum* and *Chara vulgaris*. Water was still springing as before and there is potential for the habitats to become re-established, albeit it slowly and perhaps in a depauperate state.

Large scale movements of earth were suspected to have impacted on a spring and flush site at Cookstown, near Enniskerry. This site was not seen prior to the earthworks having been carried out; it was partially recolonized at the time of inspection with *Equisetum telmateia, Cratoneuron*

filicinum, Brachythecium rivulare and *Pellia endiviifolia*. Lands close to a site of high conservation status at Eskeragh Bridge, Co. Mayo, were partly bulldozed at the time of survey; there was no obvious impact on the spring area at that time but the proximity of large scale earth movements close to such an important site is cause for concern.

Coastal defence works, for example the building of walls along the coast between Skerries and Balbriggan, while infrastructurally important, have nevertheless had negative impacts on the ecological integrity of coastal springs and seepages (Photo 6.18).

Dumping was observed at several locations. Brushwood had been discarded on top of tufa-formations at Woodlands, Broadboyne Bridge and Ballyman Glen (Photos 5.10, 6.8 and 6.30). Domestic rubbish was abandoned amongst spring communities at Kilrock Quarry, Louisa Bridge and Kiltown. Water monitoring equipment installed in Ballyman Glen was located in the midst of a tufa cascade and installation caused severe damage to the tufa deposits and their plant communities (Photo 6.31). Landscaping and cleaning activities have impacted on some tufaceous communities. A series of springs in Kilcullen Valley Park was subjected to various forms of 'tidying' and landscaping in the past, most likely through a lack of awareness of their ecological significance. Similarly, springs at the Twin Wells, Lisdoonvarna, were subjected to inappropriate building and landscaping. A small spring on Balscadden Road, Howth, was interfered with by the building of a wall and backfilling with imported soil (Photos 6.32 and 6.33).

Former excavation of inactive deposits was in evidence at Hartwell and at Marl Lough, Co. Mayo (Photo 6.34 and App. VIII). While this does not directly threaten extant spring communities, it could interfere with local hydrological patterns. Ancient deposits also hold important paleoecological records (e.g. Preece & Robinson 1982, Preece *et al.* 1986).

6.1.5 Recreational Activities

Recreational activities take place in close proximity to several sites and affect approximately 7% of the area surveyed in negative ways.

Clay pigeon shooting takes place close to Ballyman Glen and the fen was littered with the broken remains of clay pigeons (Photo 6.35). The long-term impact of these on the ecology of the fen is unknown, but their presence on the ground surface is both physically and visually intrusive.

Glencar Waterfall, Co. Leitrim attracts large numbers of visitors and a boardwalk has been constructed to guide visitors through the site (Photo 6.36). The site was not seen prior to the installation of the boardwalk; there are no obvious negative impacts arising from the present situation and it seems to be an effective way of deterring visitors from trampling sensitive areas.

Small scale trampling was in evidence at seepages at Ardmore Point and in flushes below springs at Glenasmole, but this is not impacting unduly on the vegetation at present. A hostel and adventure activities are run at Knockree close to the spring locations, but apart from a minor litter problem there was no evidence of damage at the time of site visits. However, levels of both nitrates and phosphates are somewhat elevated in the spring water and it is possible that this is related to sewage arising from the numbers of visitors using the hostel and/or adventure centre. Antisocial behaviour is frequent at Louisa Bridge, evidenced by discarded cans and bottles and excessive trampling of sensitive areas.

6.1.6 Non-native species

Non-native species are not common in Irish petrifying spring habitats. Only three such species were recorded rooted in relevés during the present study: *Epilobium brunnescens, Acer pseudoplatanus* and *Prunus laurocerasus*. *E. brunnescens* was present in five relevés (2.7%) with cover values of 0.1 to 0.5%. This low-growing, creeping willowherb is native to New Zealand and, while local in Ireland in damp habitats, it is spreading (Parnell & Curtis 2012). It is frequent in springs in the Benbulbin Range; it was also present in springs at Murlough Bay, Co. Antrim, Dooaghtry, Co. Mayo and in the Camcor Valley, Slieve Blooms. *Acer pseudoplatanus* seedlings were present in six relevés (3.2%) with cover values of 0.1 to 2%. This species was not recorded as a mature tree within spring-irrigated communities, but it has the capacity to impact spring flora by growing on adjacent dry ground and casting shade; it was present in the canopy of 12 relevés (6.5%). *Fagus sylvatica* was present in the canopy of 5.9% of relevés but it was not rooted in spring communities.

Prunus laurocerasus was recorded in one relevé (0.5%), in Coneyburrow Wood (Photo 6.37). Shortly before the commencement of this study, the area surrounding the springs in Coneyburrow Wood had been cleared of a dense shrub layer of cherry laurel by Coillte, the landowner (S. Heery, pers. comm.). Some regrowth of cherry laurel was evident at the time of survey and a resprouting shoot was present in a relevé (0.5% cover).

All four species are invasive; the three woody species, *Acer pseudoplatanus, Fagus sylvatica* and *Prunus laurocerasus* reduce plant diversity severely by shading habitats (Reynolds 2002).

Conifer plantations are located close to several sites: Kingsbog, Co. Kildare; Knockree, Co. Wicklow; Glencar, Cormac Reagh's Hole and Gleniff (Photo 6.38), in the Benbulbin Range and at several locations in the Slieve Blooms.

6.1.7 Tufa formation in modified environments

Several instances of tufa formation in anthropogenic settings were observed, besides the pipe outfalls already mentioned. Lock gates on the Grand Canal at Naas had developed interesting bryophyte-dominated tufa deposits before being cleaned (Photo 6.39). A fountain in the Japanese Gardens at Powerscourt House, Co. Wicklow, was depositing tufa and the species *Palustriella commutata, Cratoneuron filicinum, Brachythecium rivulare, Platyhypnidium riparioides* and *Pellia endiviifolia* were growing around it (Photo 6.40); part of the structure of the surrounding gardens consisted of quarried tufa. Nearby, the roadside boundary of a garden in Enniskerry village contained a small petrifying spring with *P. commutata, C. filicinum, Didymodon tophaceus, P. endiviifolia* and *Conocephalum conicum*, as well as the vascular plants *Geranium robertianum* and *Carex flacca*. An unexpected find in Glenasmole was a bath situated at a spring head (used in the past for watering cattle); its rim is now draped with *P. commutata* (Photo 6.41).

6.1.8 Natural Processes of Change

A notable feature of petrifying springs on steep hillsides is the propensity for tufa to accumulate to the point where its weight can no longer be supported and it falls downhill, leaving a scar on which the process begins again. This is a characteristic feature of the hillsides in Glenasmole and Glenbarrow, where permanent quadrats were set up to monitor change (Chapter 7, Photos 7.23 to 7.26), but it was also noted on the Benbulbin Range (near QL135) and was frequently observed at coastal locations, where large chunks of detached tufa (sometimes more than $1m^3$) were strewn along beaches (for example at Ballincar, Co. Sligo; Skerries/Balbriggan, Co. Dublin and Rathcor, Co. Louth, Photo 6.42). Similarly, detached pieces of tufa, up to approximately 50cm in length, were found in streams in the Slieve Blooms where they had been dislodged from springheads and washed downstream.

The process of seral succession of vegetation may be a feature of some sites, for example Pollardstown, Ballynafagh, Ballycurrin and Ballybannon, as shallow lakes and fens accumulate organic matter, causing the surface level to rise and eventually lose contact with the calcareous ground water. At Ballybannon, Co. Down (QL124), for example, species such as *Palustriella commutata, Scorpidium cossonii, Campylium stellatum* and *Aneura pinguis* were confined to small hollows between the more prevalent vegetation, which included *Erica tetralix,* suggesting that much of the ground surface was above the influence of ground water (Photo 6.43).

6.2 Discussion

Pollution of groundwater sources poses a serious threat to petrifying spring habitats and nutrient levels in some samples are cause for concern. It was not possible during the present study to ascertain the sources of macronutrients found in spring water, but the levels measured for several sites suggest that anthropogenic inputs are present in some of the groundwaters supplying Irish petrifying springs. The sites with the highest levels of nitrates and phosphates are close to intensively managed arable lands and golf courses; septic tanks associated with rural dwellings are also a possible source of excess nutrients. The source of the very high nitrate concentration in the Ballyman Glen sample (WS067) is unknown but it is cause for concern as this is a species-rich site of high conservation value; it has a very different species composition to other sites with high nitrate levels and if, in fact, a recent rise in nutrient levels has occurred, the conservation status of the site will almost certainly be damaged. Old landfill sites in close proximity are a possible source. The finding has been brought to the attention of the local authority and local NPWS staff and it is being investigated. It was, however, measured in a once-off sample and may be due to contamination of the sample, so further sampling at this site is advised. Similarly, levels of phosphates, sulphates and plastic debris at Fonthill are unacceptable; the local authority was notified and is investigating the source of pollution.

Petrifying springs surveyed during the present study were characterised by a steady flow of spring water (apart from a small number of exceptions, such as the Thomastown Quarry and Clonaslee sites). Numerous sites, especially those in the Slieve Bloom, Glenasmole, Hartwell and at Louisa Bridge were visited repeatedly at different times of year over the duration of this project and the flow rates observed (although not quantified) were remarkably constant. Clearly, alterations to the flow would impact on the habitats and plant communities dependent on these springs, reducing the quality or extent of the habitat. It was noted during field surveys that *Palustriella commutata* was never found in a healthy state in dry conditions; in the absence of inundation by spring water – for example where a build-up of tufa had caused lateral diversion of flow – this species always showed evidence of physiological deterioration.

Vegetation at Hartwell suggests that, in spite of high alkalinity and calcium levels, even moderate increases in nutrient levels can cause characteristic petrifying spring species to be replaced by rank species of much broader ecological range. Why this effect is so pronounced at this site and not elsewhere is unexplained by the present data. It might be related to the frequency and timing of nutrient inputs; monitoring seasonal patterns of nutrient levels might help to elucidate the explanation and provide clearer guidelines for management.

The presence of dark green algal coatings on wet, shaded tufa found in tandem with elevated phosphate levels suggests that the former may be indicative of the latter. The green filamentous alga *Vaucheria* is present at some of these sites, but the dark colour noted at some locations may arise from additional species or genera being present. This coating was noted at some German sites also, *e.g.* Urach Waterfall (Photo 6.16). Water analysis of German petrifying springs was not possible during the present study, but it would be interesting to compare their composition with those of Irish waters.

The water analysis carried out during this study indicates some of the main patterns of vegetation associated with water composition. However, each site was sampled only once (in either September 2012 or September 2013, apart from three sites sampled both years). They do not take account of seasonal patterns or fluctuations due to the timing of nutrient inputs in agricultural settings or in the management of golf courses. In addition, the nature of catchments is complex. For example, the central spring of three sampled along the coast near Skerries had much lower nitrate levels than the springs either side of it, indicating that it originated from a separate source (Photo 6.3, QL154, see also Photo 3.01); such variations could not be adequately investigated or explained in the present study.

Grazing is of importance in maintaining the stability of plant communities at many sites. It is of greatest importance at sites on level or gently sloping ground (for example, steep *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades are inaccessible to most grazers). Small sedge communities are especially threatened by inappropriate grazing levels, whether under- or over-grazed. The rare mosses, *Tomentypnum nitens* and *Catoscopium nigritum* are at risk of decline if appropriate grazing levels are not maintained at Pollardstown Fen and Dooaghtry. Further investigations are necessary in this regard to monitor these species and determine suitable grazing regimes to ensure their conservation. Most of the sites surveyed suggest that strongly tufa-forming habitats are somewhat less dependent on grazing than those that were weakly tufa forming, because few robust species show ability to thrive in them. However, the tufa cascade at Hartwell is an exception which warrants further investigation.

Much could be done to inform and educate land owners about the ecological significance of petrifying springs (and other habitats) on their lands. On the whole, landowners I spoke to during fieldwork showed considerable knowledge of the plants - including mosses – that grew on their land, without knowing species names or grasping their ecological significance. Most landowners were interested and enthusiastic to learn more. Old drains are present at several sites and, if left undisturbed, they develop species-rich spring and flush vegetation over time. Maintenance of

drains must take into account the conservation status of the habitats they contain and must seek to cause minimal damage to these communities.

The siting of conifer plantations in close proximity to high conservation status petrifying spring habitats, for example in the Benbulbin Range, is inappropriate. Harvesting timber from these sites, and subsequent rehabilitation of the land, must take into account the fragility of nearby habitats and must minimise disturbance to both the spring habitats and their water catchments.

Tufa formations in unusual, anthropogenically modified settings have a certain curiosity value; they also illustrate the fact that as long as the water chemistry is not unduly modified or the flow stopped, these habitats are to some extent resilient and capable of re-establishing themselves even after far-reaching disruption. Nevertheless, springs in such circumstances generally contain only the most common species and the loss of species-richness, loss of varied microhabitats and usually a reduction in the ground area impacted by the spring means that this capacity to reassert themselves cannot be used to justify the modification of or interference with semi-natural petrifying spring communities.

Area estimates were included in this chapter to give a preliminary indication of the extent and relative importance of various management issues. Delimiting the boundary of petrifying spring habitats is fraught with difficulty, especially for larger sites were springs occur within a more general fen habitat type. Some very small sites are excellent examples of typical habitats; some larger sites are of borderline habitat types and are not especially representative of petrifying springs. Therefore, these data must be treated with caution. In addition, area measurements do not take account of the conservation status of the habitat.



Photo 6.1: Rathcor (QL213, WS128) with 35.66 mg/l nitrate. *Palustriella commutata, Eucladium verticillatum* and *Schoenus nigricans* grow on the tufa deposits (September 2013).



Photo 6.2: Rathcor (QL214, WS129) with 34.22mg/l nitrate and with *Palustriella commutata, Didymodon tophaceus*, *Festuca rubra* and *Agrostis stolonifera* (September 2013).



Photo 6.3: Intensively farmed arable land and a golf course between Skerries (to the south) and Balbriggan (to the north), in Co. Dublin. Arrows show locations of springs from which data were collected. High nitrate levels were found in WS047 (44 mg/l) and WS048 (33 mg/l), but WS046 was low in nitrate (8 mg/l). Image from www.google.ie/maps December 2014.



Photo 6.4: Arable farmland above springs at Rathcor, Co. Louth. High nitrate levels were found in WS128 and WS129 (34 to 36 mg/l). Image from www.google.ie/maps December 2014.



Photo 6.5: Dark green/blackish algal coating on tufa dam in stream at Fonthill, in the Liffey valley, Co. Dublin (May 2013). Water contains 115 µg/l phosphate (WS138).



Photo 6.6: Alga-coated tufa in Knocksink Wood (WS057 with 52 µg/l phosphate). January 2011.



Photo 6.7: Broadboyne Bridge, Co. Meath: dark coloured algae on shaded wet tufa on upper part of cascade (WS127 with 28 mg/l nitrate and 66 µg/l phosphate). April 2010.



Photo 6.8: Broadboyne Bridge: lower part of cascade dominated by *Cratoneuron filicinum.* Brushwood has been discarded on top of the tufa formation. September 2013.



Photo 6.9: Hartwell Upr (May 2010): tufa cascade on the banks of the Hartwell River in early summer. Tufa deposits continue along the bank to both left and right of the photograph.



Photo 6.10: Hartwell Upr (Sept. 2013): the same stretch of river bank in autumn with (a) *Petasites hybridus*, (b) *Scrophularia auriculata*, (c) *Epilobium hirsutum* and (d) *Urtica dioica*.



Photo 6.11: Hartwell Upr (March 2012): *Petasites hybridus* and *Iris pseudacorus* on tufa cascade.



Photo 6.12: Tufa cascade at Hartwell Upr (May 2010) with *Palustriella commutata* (centre), *Scrophularia auriculata* (left and right), *Cirsium palustre* (centre foreground) and *Chrysosplenium oppositifolium* (left).



Photo 6.13: Intact, but black-coloured tufa dam on stream at Fonthill close to the River Liffey, Co. Dublin, April 2010.



Photo 6.14: Eroded tufa dam at Fonthill, a short distance downstream of Photo 6.13, May 2013.



Photo 6.15: Plastic debris strewn along tufa-forming stream (upstream of Photos 6.13 and 6.14) at Fonthill close to River Liffey, May 2013.



Photo 6.16: Urach Waterfall in the Swabian Alps, Germany (July 2012), with dark coloured algal coating on tufa (centre and background) – phosphate levels unknown.



Photo 6.17: Diffuse seepage along the coast at Rathcor, Co. Louth with dominant *Schoenus nigricans,* August 2013.



Photo 6.18: Tufa deposition directly below pipe outfall on the coast between Skerries and Balbriggan: loss of habitats due to channelling of water and coastal defense works. May 2013.



Photo 6.19: Drainage system running through Pollardstown Fen. Water from the fen flows north into the Grand Canal via the Milltown feeder. Image from www.osi.ie December 2014.



Photo 6.20: Small scale water abstraction at Corhawnagh, Co. Sligo causing minimal impacts on the species-rich *Schoenus* Springs within which it is located. June 2010.



Photo 6.21: Small scale water abstraction in the Burren (May 2012). The pipe carries water a short distance to a trough for watering animals and saves the spring area from excessive trampling and fouling.



Photo 6.22: Trampling and nutrient enrichment below a Burren spring where cattle congregate, with *Nasturtium officinale, Veronica beccabunga* and *Ranunculus flammula*. June 2012.



Photo 6.23: Loss of habitat at a Burren spring modified for water abstraction. June 2010.



Photo 6.24: Since the cessation of grazing at Louisa Bridge, woody species such as *Rubus fruticosus* agg. (foreground) and *Fraxinus excelsior* (beyond pool) have expanded at the expense of species-rich *Carex lepidocarpa* Small Sedge Springs (January 2008).



Photo 6.25: Manual scrub clearance at Louisa Bridge, Co. Kildare (March 2009)



Photo 6.26: Pollardstown Fen (north side), where leaf litter is accumulating in a dense mat in the absence of grazing. *Tomentypnum nitens* occurs here beneath the taller plants. Sept. 2011.



Photo 6.27: Closely grazed dune slacks at Dooaghtry where the rare moss *Catoscopium nitritum* grows amongst the vegetation in the foreground. June 2012.



Photo 6.28: Species-rich, tufa-forming *Carex lepidocarpa* Small Sedge Springs in an old drain near Naas, Co. Kildare where QL077 was recorded (June 2010).



Photo 6.29: The same drain on return visit to collect water samples (September 2012).



Photo 6.30: Dumping of brushwood on tufa cascade at Ballyman Glen (May 2012)



Photo 6.31: The same location as above in December 2012, after equipment for water monitoring was installed. (See also Photo 5.7 for condition before installation)



Photo 6.32: Before: a small road-side petrifying spring in Howth below an ash tree (Sept. 2009). A weft of *Palustriella commutata* can be seen in the centre of the photo and again below.



Photo 6.33: After: a retaining wall was built along the road, backfilled with imported soil and subsequently planted with non-native species. November 2010.



Photo 6.34: Inactive tufa deposits at Marl Lough, Co. Mayo, which have been quarried in the past. October 2009.



Photo 6.35: The ground surface at Ballyman Glen, littered with broken clay pigeons, May 2012.



Photo 6.36: Managing visitor pressure at Glencar Waterfall: A boardwalk guides visitor movements to minimise damage to sensitive areas. May 2010.



Photo 6.37: Coneyburrow Wood, Slieve Bloom Mts where cherry laurel (*Prunus laurocerasus*) was cleared. Some regeneration of cherry laurel (right of photo) is taking place. May 2012.



Photo 6.38: Conifer plantation abutting waterfall with rare moss species at Gleniff on the north slopes of the Benbulbin Range. July 2012.



Photo 6.39: Lock on Grand Canal (Naas and Corbally branch, Aug. 2009) with *Bryum pseudotriquetrum, Cratoneuron filicinum, Brachythecium rivulare* and *Pellia endiviifolia* on tufa.



Photo 6.40: A fountain in the Japanese Gardens, Powerscourt House, Co. Wicklow, *with P. commutata, C. filicinum, B. rivulare, P. riparioides* and *P. endiviifolia*. March 2013.



Photo 6.41: An old bath at Glenasmole, used in the past for watering cattle, is draped with *Palustriella commutata* (October 2009). *Equisetum telmateia* is in the foreground to the left.



Photo 6.42: Detached, inactive tufa on the beach at Rathcor, Co. Louth. September 2013.



Photo 6.43: Ballybannion ASSI Co. Down. Gorse and heathers predominate; *Cratoneurion* species were confined to some small, low-lying hollows. September 2013.



Photo 6.44: Tufa-rimmed pools at Pamukkale, Turkey, August 2013. Visitors line the access route but are no longer allowed to bathe in these pools. Bathing still takes place in pools at the margins of the deposits.



Photo 6.45: Incessant crowds leave their mark; plastic bottles become incorporated into the rapidly forming tufa. August 2013.



Photo 6.46: A tufa 'catwalk' extends from the main tufa deposits to the town of Pamukkale. August 2013. (See Photos 4.9 to 4.11 for Swabian example of this feature.)



Photo 6.47: The travertine surface is remarkable, not just for its ability to advance rapidly, but for the pure white colour and the delicate powdery texture of the surface. August 2013.

7. Dynamics of Petrifying Springs

7.0 Introduction

Tufa deposits contain a stratigraphic record that can be used to investigate past biotic, climatic, hydrological and other environmental conditions (*e.g.* Preece & Robinson 1982, Preece *et al.* 1986, Pentecost 1999, Andrews 2006, Rainey & Jones 2007). The mineralogy, porosity and laminar structure seen in the sections of deposits can be informative (*e.g.* Pentecost 2005, Forbes *et al.* 2010, Keppel *et al.* 2011, Manzo *et al.* 2012). Improving our understanding of modern processes of deposition facilitates more accurate interpretations of ancient analogues (Pentecost 1987b). Deposition of tufa is highly variable depending on localised environmental and biotic conditions, especially those related to the aeration of water and outgassing of carbon dioxide (*e.g.* Chafetz *et al.* 1991, Wright 2000, Zhang *et al.* 2001 and Chen *et al.* 2004). Photosynthesis by bryophytes and algae, as well as the presence of mucilaginous microbial films on the surfaces of both living and dead organic matter, such as fallen leaves and twigs, promote tufa formation (*e.g.* Emeis *et al.* 1987, Pentecost 1996, Golubić *et al.* 2008). Deposition rates are often measured as height increases, but they can be measured in other ways, for example, as mass increases (*e.g.* Pentecost & Coletta 2007, Keppel *et al.* 2011).

A review of over 40 published studies along with some unpublished data found a mean annual deposition rate of 5.28mm per year (n=55, SD=6.32mm/yr, Pentecost 2005). Tufa associated with bryophytes accumulated at a faster than average rate of 8.7mm/yr. The mean deposition rate associated with eukaryotic algae was 9.1 mm/yr but with the green alga, *Vaucheria*, a rate of 14.7 mm/yr was reported. More recently, studies of fluvial tufa (using submerged limestone tablets) in north-eastern Spain found mean annual deposition rates of 7.85mm/yr in the River Piedra and 5.51mm/yr in the River Añamaza (Arenas *et al.* 2014 and Auqué *et al.* 2014). The former study was carried out over a thirteen year period, the latter over three years. Tablets were submerged for six months, removed briefly for measuring and replaced at the same location. Both studies reported that accumulation was most rapid in fast flowing stretches of water where tufa formed in association with cyanobacteria: 13.75mm/yr and 18.27mm/yr (Rivers Piedra and Añamaza respectively). Spongy tufa on cascades and water falls with algae and bryophytes also accumulated at an above average rate on these two rivers: 8.25mm/yr and 8.32mm/yr respectively. The slowest accumulation rates were recorded on stretches with low slope and with slow-flowing water, and in the spray zones near waterfalls. Both studies showed that fluvial tufas accumulate more rapidly in warm seasons than in cool seasons. Short term in-situ experiments in Plitvice National Park, Croatia, found that nutrient enrichment did not impede tufa deposition,

and P-enrichment even enhanced calcite deposition, probably as a result of a denser autotrophic periphyton matrix (Kepcija *et al.* 2011).

Bryophyte growth rates are often measured as shoot length increases. An annual increment of 50mm is not uncommon in *Sphagnum* shoots but other mosses typically show more modest increases in the range of 2 to 25mm/yr (*e.g.* Clymo 1962, Zechmeister 1995, Asada *et al.* 2003, Pouliot *et al.* 2010, Armitage *et al.* 2012). Data for growth rates of the bryophyte species associated with tufa are scarce. Pentecost (1987b) measured the growth of four mosses on tufa in North Yorkshire. *Platyhypnidium riparioides* grew rapidly, the shoots extending by 16mm on average over a three month period (April – July, n=11). *Palustriella commutata* grew in an erratic manner; some branches put on no new growth over a twelve month period, while others elongated rapidly or produced fast growing side shoots. The maximum growth rate recorded for this species was 3.7mm in 2.5 months (early July to late September, n=7). *Hymenostylium recurvirostrum* grew by 0.96mm one year and 2.15mm the next (n=45 and 25 respectively), while *Eucladium verticillatum* increased by 3.9mm/yr (single sample only). These measurements were made by variously tagging shoots with cotton, by inserting plastic bristles into moss cushions as height markers and by measuring scaled photographs.

Algae and cyanobacteria associated with tufa are often slow growing but, again, there is high variability. The green alga *Gongrosira*, heavily encrusted with calcite, put on an annual radial growth of 0.42mm and growth was positively correlated with water temperature (Pentecost 1988), while the cyanobacterium *Rivularia haematites* grew 12-14µm d^{-1} in summer (equivalent to 2.4mm in six months) and <2 µm d^{-1} in winter. Calcification associated with the unicellular desmid *Oocardium stratum* produced seasonal laminae 4-8mm in thickness, with a maximum annual height increase of 10mm (Sanders and Rott 2009).

Two aspects of the dynamics of petrifying springs were investigated during the present study: the rate of tufa accumulation, and the process of plant colonisation on newly forming tufa surfaces.

7.1 Methods

7.1.1 Tufa accumulation rates

A novel approach to measuring tufa accumulation rates was adopted in this study. Dr P. Johnston, TCD, suggested setting up a horizontal structure spanning tufa deposits and measuring vertically downwards from this to the tufa surface. The structures were designed and made by R. Lyons, Omos Ltd: stainless steel box section bars were mounted horizontally over actively growing tufa deposits (Table 7.1, Photo 7.1). The bars were clamped securely to angle irons which had been hammered into dry ground on either side of the tufa to a depth of approximately 600mm. Prior to installation, crossbars were drilled at 50mm intervals with a 6.5mm drill bit, allowing a stainless steel rod (6mm diameter) to fit snugly in the hole but be free to slide with minimal friction (Photo 7.2).

Table 7.1: Materials for measuring bars

Item	Material	Length
Uprights	25mm x 25mm x 3mm angle iron (or 10mm threaded bar)	1000mm
Cross bar	25mm x 25mm x 1.5mm box section 304 grade stainless steel	850 – 2300mm
Nuts and Bolts	M8 zinc plated hex bolts and nuts	
Measuring rod	6mm diameter stainless steel rod	500mm

Locations were selected where the bars could be installed above active, consolidated tufa deposits and where there was dry, stable ground on either side of the zone of deposition to provide secure anchorage. Other criteria in the selection of sites included avoiding damage to sensitive sites, obtaining permission from landowners, choosing locations which were unlikely to be interfered with by members of the public and ensuring that sites were accessible for making repeated measurements. Fourteen bars were installed securely; they measured from 850mm to 2300mm in length. They were located at Glinsk Grove and Coneyburrow Wood in the Camcor River valley, Slieve Bloom Mountains, Co. Offaly; at Glenasmole and on the coast north of Skerries, Co. Dublin; at Hartwell, near Naas, Co. Kildare; and in Knocksink Wood, Co. Wicklow (Table 7.2). A fifteenth bar measuring 4730mm in length (Bar 9, Hartwell) was installed; however, due to its length, it flexed rather than remaining rigid and it was not used for making measurements. At one site (coast north of Skerries), it was necessary to anchor the bars in bedrock (and a retaining wall). Instead of using angle irons, the rock was drilled, threaded bars (10mm ø) were cemented into the rock and the crossbar was fixed to these (Photo 7.3).

Table 7.2: Tufa accumulation measurement sites

Site	Region	Landscape Setting	No. of Bars
Coneyburrow Wood	Slieve Bloom Mts	Woodland Hillside	2
Glinsk Grove	Slieve Bloom Mts	Recolonising Woodland	3
Glenasmole	Co. Dublin	Woodland Hillside	3
Hartwell	Co. Kildare	Farmland River Bank	2
Knocksink Wood	Co. Wicklow	Woodland Hillside	2
Skerries Coast	Co. Dublin	Coastal Spray Zone	2

Measurements were made in March each year from 2011 to 2013 inclusive. The 6mm stainless steel rod was lowered through each hole of the crossbar in sequence and the length of rod above the bar was measured (to the nearest mm) for:

1. The first point at which the rod made contact with a bryophyte (if present),
2. The point at which the rod touched the surface of water (if present),
3. The final position at which the rod rested under its own weight.

The last measurement was taken to be the height of the surface of the tufa deposit (Photo 7.2). All species of bryophytes making contact with the rod were noted. While resting on the surface, it was noted if the rod was in contact with leaf litter (either in situ litter/standing dead or ex situ litter) and/or with bare tufa (consolidated, unconsolidated or encrusted on plants). Holes at either end of the bar overlying soil rather than tufa were excluded. A relevé was recorded at each bar location; these are contained within the main relevé data set.

As a separate means of making measurements, markers were inserted into tufa deposits at a number of locations to see if tufa accumulation and/or bryophyte growth could be measured in this way. This provided a cheaper and more flexible approach as not all sites are suitable for installing bars. Two kinds of inert markers were used, depending on the species being measured. Plastic plant labels (125mm long, Photo 7.17 and 7.18) were inserted into low-growing moss turfs and liverwort thalli; the shoot or thallus lobe closest to the labelled side of the marker was measured, relative to the top of the marker. Ertalon[1] rods (500mm long, 10mm diameter, Photo 7.19 and 7.20) were used in deeper *Palustriella commutata* wefts; the distance from the top of the marker to the highest point at which the species touched the rod was measured.

[1] Ertalon is a tough, inert, synthetic material available from Amari Ireland Ltd.

7.1.2 Recolonisation on Landslide Sites

At the beginning of fieldwork, a number of sites had experienced recent landslides (within the previous 2 years) and were in the early stages of recolonization, with some incipient tufa formation. Two of these landslides covered large areas (several hundred square metres, at Glenasmole and Glenbarrow); others were small slippages (<20 m^2, Glinsk and Glenbarrow). Eight 2 x 2m permanent quadrats (PQs) were set up: four at Glenasmole, three at Glenbarrow and one at Glinsk. Vegetation and abiotic characteristics were recorded every March (following the same procedures as for the main relevé records) from 2011 to 2014 inclusive.

Data from permanent quadrats on landslides were compared with relevés on stable ground within the same spring complexes (contained in the main relevé data set): 20 relevés from Glenasmole, 6 from Glinsk and one from Glenbarrow were used for comparisons.

7.1.3 Statistical Analysis

Data collected from the stainless steel bars were analysed using linear mixed effects models. This provides a flexible approach for analysing non-normal data when random effects are present and when samples are not independent of each other (Bolker *et al.* 2008). Random effects, in this case, arise from bars nested in springs (or sites). In contrast, fixed effects (the factors of interest) are variables such as the presence or absence of bryophytes – as a group, or by individual species – the presence or depth of water and the presence of leaf litter. Mixed models allow random effects and fixed effects to be handled separately. Random factors are given different intercepts to take account of baseline differences between them. Random slopes can also be specified in the model to allow for differences in the effects of an individual fixed factor. For example, the effect of a particular species at one bar may be different to its effect at another, due to some factor not included in the model, perhaps shelter or competition from other species. Introducing random slopes takes this into account and reduces the chance of a Type I error (Barr *et al.* 2013). The Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) are calculated for each model tested. These are both measures of goodness of fit versus model complexity (each makes the calculations in a slightly different way). The more variance within the system explained by the model, and the simpler the model, the lower the AIC and BIC values will be (Zuur *et al.* 2009).

A null model is constructed, omitting the factors we wish to test. Factors of interest are then entered into models, either separately or in combination, with or without interactions. The AIC

and BIC values are inspected and the new model is tested against the null model using a chi-squared test. For comparison purposes, models are run using Maximum Likelihood. When the optimal model is finally selected, it is rerun using Restricted Maximum Likelihood (REML) which estimates the contribution of each factor and each interaction, calculating standard deviations in a slightly different way to the initial Maximum Likelihood run (Bolker *et al.* 2008).

7.2 Results

The mean annual change in the surface height of tufa deposits was an increase of 20.5 ± 1.1mm, measured across 293 samples (Table 7.3). The mean rate of accumulation in the first year was slightly higher than in the second (22.4mm compared to 18.6mm); a Wilcoxon signed rank test found that the difference between the two years is not statistically significant ($p>0.05$).

Tufa accumulation rates varied widely between bars, even between bars on the same spring (Fig. 7.1). The biotic and abiotic characteristics of the various locations are also very different. Profiles recorded by each bar are shown in App. VI. The bar with the most rapid rate of deposition (Bar 14, Skerries, 33.0mm/year, Photos 7.3 and 7.4) recorded a mean height increase 5.5 times greater than that recorded by the bar with the slowest rate (Bar 6, Glenasmole, 6.0mm/year, Photos 7.7 and 7.8). There was an almost three-fold difference between the two Skerries bars (Bars 14 and 15), which were located on coastal springs 1.1km apart. Within springs, the greatest difference between bars was at Glenasmole, where there was a four-fold difference between the greatest and least mean bar height changes. The bars at Glenasmole were located in sequence with distance from the springhead; the greatest mean bar height change was recorded at the middle bar (Bar 7) and the least at the bar most distant from the springhead (Bar 6). At both Knocksink and Glinsk (east), the difference within the pairs of bars was more than double. In both cases, the growth rate was faster at the bar more distant from the springhead (Bar 4 and Bar 13).

Surface water was present in 19.6% of samples. The maximum depth of water recorded was 168mm, but most samples had a depth of less than 50mm (87% of samples in which water was present). The bars spanning the wettest tufa deposits were located in Glenasmole and Hartwell. Bars 6 and 11 had most water, both in cover (number of samples) and in depth, but had very different rates of deposition (6.0mm compared with 24.4mm). Both contained v-shaped channels (App. VI). The channel at Glenasmole was deeper and contained faster flowing water (visual estimate; flow rates were not measured), so that the potential for erosion was greater here than at Hartwell where the tufa cascade surface is more gently sloping.

Small amounts of surface water were present beneath the bars at Coneyburrow, Glinsk, Knocksink and Skerries. Rivulets averaged 9.6mm in depth and they shifted laterally from year to year as the microtopography was altered by newly deposited tufa. Overall, the cover by water at these four sites decreased from March 2011 to March 2013 by 62% as shifting flow patterns caused water to bypass the bars. Conversely, cover by water doubled during this period at Glenasmole and Hartwell.

Table 7.3: Results for each bar from March 2011 to March 2013. TB is the bar reference code. n = number of holes, excluding those impacted by edge effects described in text. Mean Water Cover is the percentage of samples (holes) at which water was present (≥1mm depth) over the three measuring periods. Plant Community numbers refer to fuzzy cluster groups (Chapter 3).

TB	Bar Name	n	Annual Height Change (mm)		Mean Water Cover	Mean Water Depth (mm)	Plant Community ($4m^2$ Relevé)
			Mean	S.E.			
1	Coneyburrow dam bar	32	12.5	1.8	2%	0.2	2
2	Coneyburrow cascade bar	30	20.0	2.4	7%	0.2	3
3	Glinsk (east) upper bar	9	12.8	2.0	4%	0.4	2
4	Glinsk (east) lower bar	19	30.8	3.3	25%	3.4	2
5	Glinsk (west) bar	23	17.6	2.7	0%	0.0	2
6	Glenasmole lowest bar	6	6.0	3.0	78%	43.3	3
7	Glenasmole middle bar	20	24.2	5.0	63%	9.3	3
8	Glenasmole upper bar	12	11.3	2.9	61%	18.9	3
10	Hartwell long bar	16	28.0	5.4	58%	21.0	3
11	Hartwell short bar	5	24.4	5.6	73%	32.3	3
12	Knocksink upper bar	25	10.0	0.8	9%	1.0	2
13	Knocksink lower bar	34	27.2	4.3	12%	1.2	2
14	Skerries long bar	37	33.0	3.7	10%	0.9	4
15	Skerries short bar	25	11.6	1.8	8%	0.4	3
Total	**14 Bars**	**293**	**20.5**	**1.1**	**19.6%**	**4.5**	

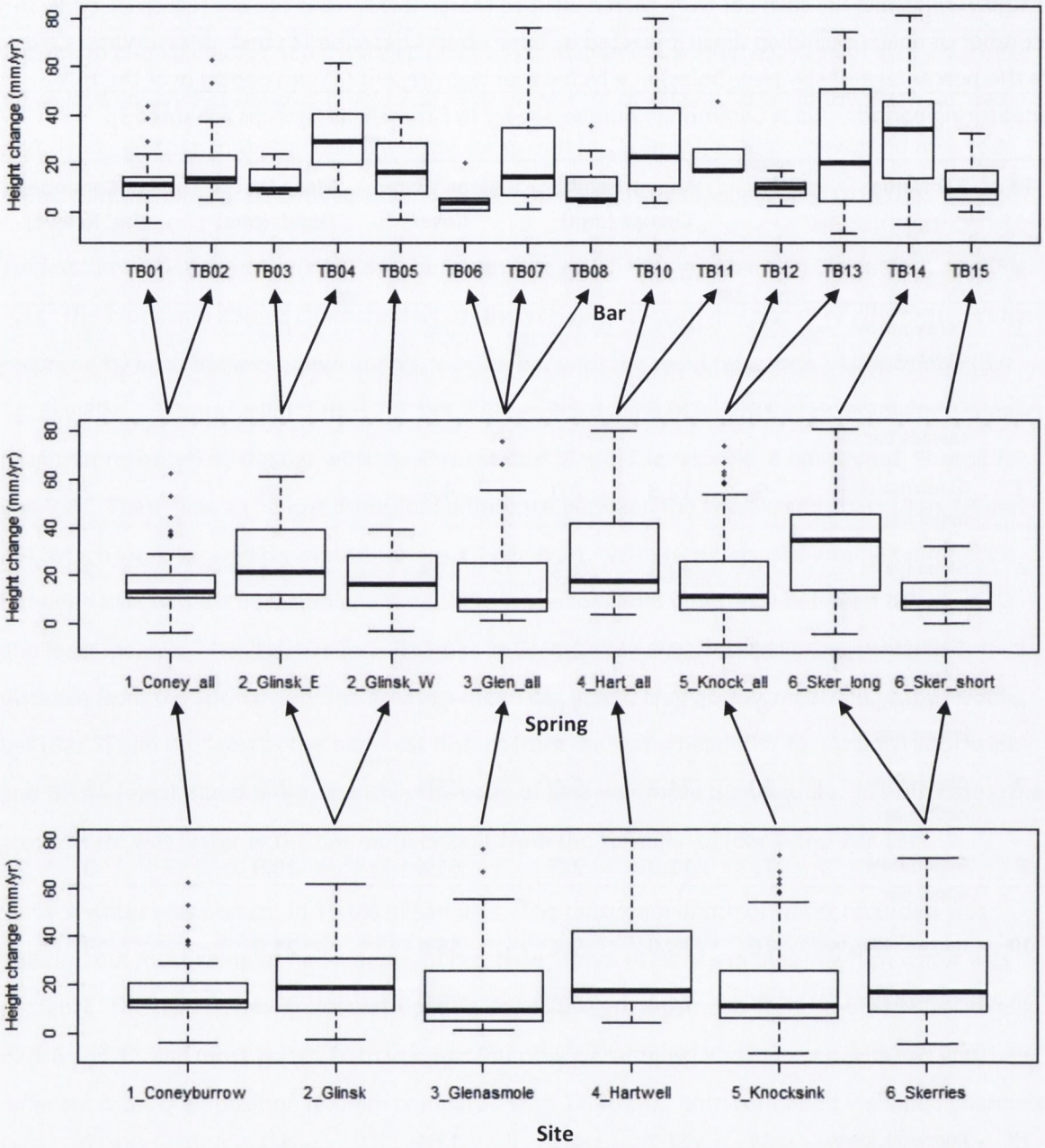


Fig. 7.1: Mean annual height change (2011 – 2013) showing the arrangement of bars in springs, and springs in sites.

7.2.1 Bryophyte growth

79% of samples contained bryophytes (*i.e.* 79% of rod measurements made contact with live bryophyte shoots). *Palustriella commutata*, the most frequently occurring species, was present in 43% of records. In 32% of samples (n=92), it was the sole species recorded in all three consecutive measurements and for these samples the mean tufa surface height increase was 24.2 ± 2.1 mm/yr (Table 7.4). Vegetation height measurements (the point at which the rod first made contact with a living bryophyte, as opposed to the position where it finally rested) suggest that *P. commutata* may attain height increases in excess of the surface accumulation rate. Vegetation height measurements from the bars, combined with independent measurements of species growth rates made using Ertalon markers, estimate the average annual height increase of *P. commutata* wefts to be 27.6 ± 1.9 mm (n=135). See, for example, Photos 7.19 and 7.20 of Ertalon markers at Glinsk.

Table 7.4: Summary of growth rates associated with individual species. Tufa deposition rates are bar surface height measurements. Species growth rates are combined vegetation measurements made using both bars and plastic/Ertalon marker measurements; growth rate is vertical height increase. Th. liverwort = thallose liverwort.

Species	Growth Form	Tufa deposition rate (mm/yr)			Species growth rate (mm/yr)		
		Rate	SE	n	Rate	SE	n
Palustriella commutata	Pleurocarp	24.2	2.1	92	27.6	1.9	135
Didymodon tophaceus	Acrocarp	9.7	1.7	17	9.1	1.6	38
Eucladium verticillatum	Acrocarp	17.9	5.8	10	9.5	1.3	22
Cratoneuron filicinum	Pleurocarp	10.4	5.8	5	46.9	4.2	8
Pellia endiviifolia	Th. liverwort	22.3	4.7	6	17.7	3.2	18
Conocephalum conicum	Th. liverwort	na	na	na	21.3	9.4	6

Other species were present with low frequencies. Those which occurred most often were *Didymodon tophaceus* (10% of samples), *Cratoneuron filicinum* (8%), *Conocephalum conicum* (7%), *Eucladium verticillatum* (6%) and *Pellia endiviifolia* (5%). *Didymodon tophaceus* was the sole species for three consecutive records in 6% of samples; these showed a mean surface height change of 9.7 ± 1.7 mm/yr. The mean annual growth rate of this species was estimated to be 9.1 ± 1.6mm (n=38, combined bar and plastic marker vegetation measurements with outliers removed, detailed below). The mean annual growth rate for *Eucladium verticillatum* was 9.5 ± 1.3mm (n=22). The remaining species have high standard deviations associated with both tufa

surface height and vegetation height changes (Table 7.4). Estimates suggest that the growth rates for the thallose liverworts *Pellia endiviifolia* and *Conocephalum conicum* are somewhat greater than those of the acrocarps, *D. tophaceus* and *E. verticillatum*, but less than the pleurocarps, *P. commutata* and *Cratoneuron filicinum;* however, there is much uncertainty due to the small sample size. There is some evidence that *C. filicinum* can attain very rapid growth rates – a mean value in excess of 40mm/yr was recorded for a weft of this species at Glinsk[2].

The uneven surface of bryophyte colonies being measured gave rise to some erratic measurements; a small proportion of values were negative. Eleven measurements for *P. commutata* were treated as outliers and not included in the growth rate estimates above (Table 7.5). In two outlying samples, a height decrease of 45 and 60mm was recorded; in nine samples, there were height increase of between 107 to 199mm. Three measurements for *D. tophaceus* were treated as outliers (increases of 36 to 42mm) and there was one outlying measurement for *E. verticillatum* (65mm). All measurements treated as outliers are greater than two standard deviations from the mean; excluding them gives more conservative estimates of growth rates.

Table 7.5: Outlying measurements for bryophyte growth rates.

Species	Valid Measurements				Outliers	
	n	Mean	SD	Range	n	Range
D. tophaceus	38	9.1	10.1	-9 to 32 mm	3	36 to 42 mm
E. verticillatum	24	12.4	11.7	1 to 45 mm	1	65 mm
P. commutata	135	27.6	22.6	-28 to 95 mm	2	-45 to -60 mm
					9	107 to 199 mm

[2] Recorded at four samples of a single weft on Bar 5 Glinsk (west) for two consecutive years (annual height change ranged from 36mm to 71mm).

7.2.2 Relationships with other factors

Modelling tufa deposition using mixed effects confirms that deposition rate increases in the presence of *Palustriella commutata* ($p<0.001$). Furthermore, rates are significantly affected by the interaction between *P. commutata* and the presence of surface water, and there is a significant though less well defined interaction of these two factors with alkalinity and nitrate levels.

The interaction between the presence of *Palustriella commutata* and surface water affects annual deposition ($\chi^2(5)=45.03$, $p=1.433 \times 10^{-8}$), increasing it by 5.7 ± 1.9mm. This is the optimal model to explain the data collected using the bars (m33, Table 7.6 below); it is very highly significantly different to the null model, it produces the lowest BIC score and the AIC score is also low compared to other models. According to this model, in the absence of both *P. commutata* and surface water, the mean annual height increase is 15.4mm ± 2.9mm. *P. commutata* (without surface water) increases this rate by 2.4 ± 1.0mm/yr, while surface water (without *P. commutata*) increases it by 0.2 ± 2.6mm/yr.

Adding to this model an interaction with alkalinity and nitrate shows that these factors have a statistically significant effect (m36 compared to m33, $p<0.01$), but the BIC value indicates that the more complex model is not justified as it makes only a small additional contribution to explaining variance within the system. A comparison of bars within the same site, for example, at Knocksink (TB12, TB13) or Glinsk (east) (TB3, TB4), shows that the same levels of alkalinity and nitrate can produce very different deposition rates (Table 7.7 below). Nevertheless, this model (m36) illustrates some interesting effects of alkalinity and nitrate: (1) the effect of alkalinity (on its own or in combination with *P. commutata* and/or surface water) is greater than that of nitrate, as might be expected; (2) the effect of alkalinity is greatest in the presence of surface water; (3) the effect of nitrate is greatest in the presence of *P. commutata*.

The presence or absence of surface water has a greater effect on deposition than water depth within the ranges present (m13 has lower AIC and BIC values than m14).

Table 7.6. Assessing the relationship of biotic and abiotic variables with tufa accumulation rates. Models were compared to the null model (m00, Pr(>Chisq)). The optimal model is m33. Height = annual change in mm from 2011 to 2013; Pcom = *Palustriella commutata* presence/absence; bryos = presence/absence of all species of bryophytes combined; water_cov = presence/absence of surface water; litter = leaf litter and standing dead; alk = alkalinity.

Ref	Model	AIC	BIC	df	Pr(>Chisq)
m00	height~1 + (1|bar)	2502	2513		
m03	height~1 + (1|spring/bar)	2504	2519		
m10	height~bryos + (1+bryos|bar)	2492	2515	3	**
m12	height~Pcom + (1+Pcom|bar)	2491	2513	3	***
m13	height~water_cov + (1+water_freq|bar)	2484	2506	3	***
m14	height~water_depth + (1+water_depth|bar)	2497	2519	3	*
m16	height~litter + (1+litter|bar)	2500	2522	3	*
m33	height~Pcom*water_ cov + (1+water_freq|bar)	2467	2496	5	***
m34	height~Pcom*water_ cov*alk + (1+water_freq|bar)	2465	2509	9	***
m36	height~Pcom*water_ cov*alk*nitrate + (1+water_freq|bar)	2463	2537	17	***

The null model used was the change in height as a function of the random factor, 'bars' (m00, Table 7.6). Boxplots show that height change is more variable between individual bars than between springs or sites and using the individual bars as the random factor resulted in lower AIC and BIC values than if spring, site or a nested combination of these factors was used (*e.g.* m03, Table 7.6). As well as random intercepts, 'bars' were given random slopes for the effect being tested, because these effects may vary from bar to bar depending on variables which have not been accounted for in the model, for example the flow rate of water. In the optimal model, m33, randomising the slope by water cover gives lower AIC and BIC values than randomising it by *P. commutata*.

The mean values for deposition rates of individual bars are plotted against other variables in Fig. 7.2 below (see Tables 7.3 and 7.7 for data). These plots suggest some weak relationships between height change and other variables, but the relationships are far from convincing. Testing single factors in mixed effects models shows that the presence of bryophytes in general (all species combined), depth of water and presence of leaf litter are associated with effects on height change ($p<0.05$) but they make only small contributions to explaining the overall variance (m10, m14, m16, Table 7.6). Species of bryophytes other than *P. commutata* did not have a significant effect on height (but sample sizes are small). No significant effect was found for water chemistry

parameters as single factors (although alkalinity and nitrate are significant in the interactions described above).

Table 7.7: Bryophytes, leaf litter and water composition at each bar. Data are mean annual frequency (presence/absence in sample) of bryophytes and leaf litter. Alkalinity and nitrate values are from the analysis of a single water sample per bar (or for two or three nearby bars irrigated by the same stream of water).

TB	Height Change (mm/yr)	Bryophyte Frequency (All species)	*P. commutata* Frequency	Bryophyte Frequency ex. *P. commutata*	Leaf Litter Frequency	Alkalinity mg/l HCO_3^-	Nitrate mg/l
1	12.5	91.7%	56.3%	35.4%	39%	285	0.8
2	20.0	53.3%	0.0%	53.3%	83%	293	1.2
3	12.8	100%	96.3%	3.7%	59%	247	4.2
4	30.8	100%	89.5%	10.5%	74%	247	4.2
5	17.6	98.6%	63.8%	34.8%	64%	329	3.6
6	6.0	0.0%	0.0%	0.0%	28%	280	2.9
7	24.2	11.7%	0.0%	11.7%	28%	280	2.9
8	11.3	27.8%	2.8%	25.0%	25%	280	2.9
10	28.0	4.2%	0.0%	4.2%	4%	397	14.0
11	24.4	6.7%	0.0%	6.7%	7%	397	14.0
12	10.0	81.3%	77.3%	4.0%	47%	386	8.0
13	27.2	81.4%	81.4%	0.0%	58%	386	8.0
14	33.0	75.7%	55.9%	19.8%	80%	304	44.1
15	11.6	78.7%	0.0%	78.7%	13%	358	33.0

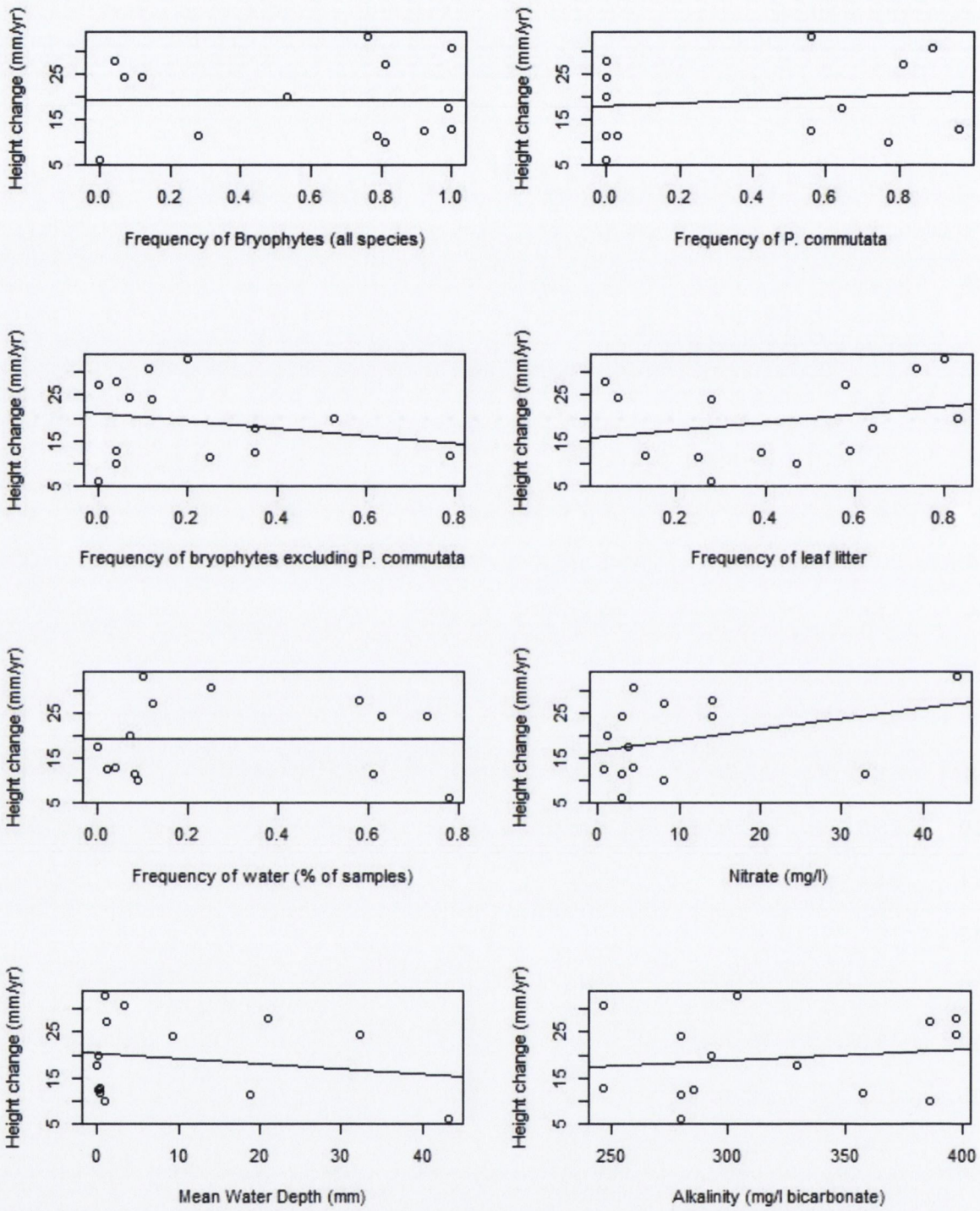


Fig. 7.2: Relationship between mean annual height increase for each bar and other variables. Frequency data are the proportion of samples in which the variable was present over the entire sampling period.

7.2.3 Plant communities

The vegetation at bar locations belongs to three communities (Table 7.3 above):

- *Palustriella commutata – Geranium robertianum* Springheads (Group 2; Section 3.2.2)
  - 6 bars: Glinsk, Knocksink and Coneyburrow Wood
- *Brachythecium rivulare – Platyhypnidium riparioides* Tufaceous Streams & Flushes (Group 3; Section 3.2.3)
  - 7 bars: Glenasmole, Hartwell, Coneyburrow Wood and Skerries
- *Palustriella commutata – Agrostis stolonifera* Springheads (Group 4; Section 3.2.4)
  - 1 bar: Skerries

There is no significant difference in deposition rates among the communities in this sample (Fig. 7.3). The range of deposition rate measurements in Groups 2 and 3 is very similar. Group 4 has the highest median value, but this group is represented by only a single bar (TB14, the bar with the most rapid deposition rate).

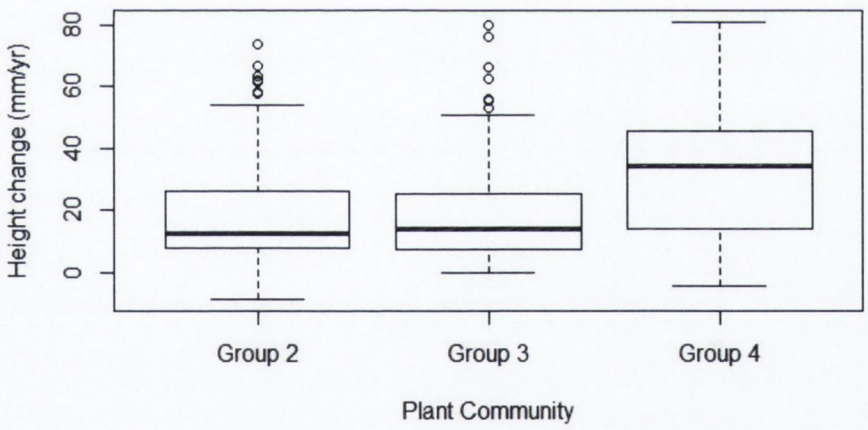


Fig. 7.3: Tufa deposition rate in three petrifying spring plant communities:
Group 2 *Palustriella commutata – Geranium robertianum* Springheads;
Group 3 *Brachythecium rivulare – Platyhypnidium riparioides* Tufaceous Streams & Flushes;
Group 4 *Palustriella commutata – Agrostis stolonifera* Springheads

7.2.4 Measurement issues

In 6% of samples (19 samples, all at Bar 8 Glenasmole and Bar 11 Hartwell) tufa deposits rose above the height of the crossbar during the second year. These were omitted from all analyses as the presence of the bar began interacting with the accumulation process during the monitoring period. In Glenasmole, this was partly due to the bar acting as a dam for plant debris being washed downstream, thus creating additional surfaces on which tufa could form (Photos 7.9 and 7.10). In Hartwell, grasses at either side of the bar grew over it and tufa formed on the grass stems (Photos 7.15 and 7.16). Samples exceeding the height of the crossbar are shown with a dashed line in profiles (App. VI).

One outlying value from Bar 11, Hartwell, was omitted from the analysis. It recorded a mean annual tufa height increase of 155mm. The cascade at Hartwell has a very uneven surface and deposition takes place in a complex, 3-dimensional microtopography (Photo 7.15). As steep parts of the surface accumulate, they advance forwards (in the direction of water flow) so that, in some samples, the accumulation rate is exaggerated by measuring in a vertical plane rather than perpendicular to the plane of deposition. This contributed to the extreme height change recorded at Bar 11. However, rapid vertical growth rates were verified at Hartwell by short-term measurements using two Ertalon rods inserted into tufa associated with the green alga *Vaucheria* sp. These recorded a mean increase of 136mm in a seven month period, from August 2011 to March 2012 (Photos 7.21 and 7.22).

Samples located at either end of the bars were omitted from the final data set due to ambiguities caused by tufa deposition petering out gradually and where vegetation of adjacent habitats interfered with the measurement process; for example, stems and leaves of plants (especially graminoids, such as *Juncus effusus*) often lay across the edges of tufa deposits, even though they were not rooted within tufa-forming communities. 107 potential samples were omitted from the final analysis for these reasons.

All fourteen bars remained secure with no signs of movement or interference up to March 2013. In the year that followed however, all but one bar became unusable and measurements were abandoned (Table 7.8 below). The tufa deposits on the coast near Skerries suffered the impacts of severe storms during the winter of 2013/2014. One bar (Bar 14) was washed away along with part of the tufa cascade, leaving only a threaded bar cemented into the bedrock (Photo 7.5 and 7.6). The other bar (Bar 15) was damaged and twisted. At Glenasmole, two bars had become overtopped by tufa (and one had been partly bypassed by the stream of water as early as March 2012, Photo 7.11). The three bars at Glinsk became overgrown with *Juncus effusus* and *J. inflexus* rooted at the edges of the tufa and falling across the deposits in dense mats (Photo 7.13 and

7.14). This site had been clear-felled of a conifer plantation in 2006 (Heery & McCorry 2010) and rapid successional changes were occurring in the ground flora in the absence of tree canopy. The tufa deposits had also been partly trampled by deer (Bar 4) since they provided a somewhat easier passageway through the dense growth of rushes. The bars at Hartwell had become progressively overgrown with vascular plants, especially the grasses *Holcus lanatus* and *Agrostis stolonifera,* encroaching from the sides and lying on top of the bars (Photos 7.15 and 7.16). Both bars at Coneyburrow and both at Knocksink showed signs of drying out as water diverted down other parts of the hillside.

Table 7.8: Condition of bars three years after installation (March 2011 - 2014)

TB	Bar Name	Condition of Bar in March 2014
1	Coneyburrow dam bar	Drying out, flow of water diverting laterally
2	Coneyburrow cascade bar	Drying out, flow of water diverting laterally
3	Glinsk (east) upper bar	Overgrown by dense *Juncus* growth, not rooted on tufa
4	Glinsk (east) lower bar	Overgrown by dense *Juncus* growth, not rooted on tufa
5	Glinsk (west) bar	Overgrown by dense *Juncus* growth, not rooted on tufa
6	Glenasmole lower bar	In situ, no signs of damage or interference
7	Glenasmole middle bar	Overtopped by tufa, partly bypassed by stream of water
8	Glenasmole upper bar	Overtopped by tufa
10	Hartwell long bar	Overgrown by grasses encroaching from sides
11	Hartwell short bar	Overgrown by grasses encroaching from sides
12	Knocksink upper bar	Drying out, flow of water diverting laterally
13	Knocksink lower bar	Drying out, flow of water diverting laterally
14	Skerries long bar	Washed away in winter storms
15	Skerries short bar	Twisted by winter storms

7.2.5 Recolonisation of landslides

Incipient tufa formed in the aftermath of landslide events was rapidly colonised by the small acrocarps *Dicranella varia* and *Pohlia melanodon*. These were often the most abundant species in permanent quadrats in the early stages of monitoring (Fig. 7.4, Photos 7.27 and 7.28). Both reached their maximum mean cover in the second year of monitoring (2-3 years after the landslide occurred), occupying on average 6.4% and 7.6% of the ground surface respectively[3]. In contrast, they were seldom recorded in quadrats on stable ground and, where present, they occupied very small areas (Table 7.9). *Funaria hygrometrica* was recorded occasionally in landslide quadrats, but in smaller amounts; it was not present in any quadrats on stable ground. *Pohlia wahlenbergii* was also more abundant in landslide quadrats than in those on stable ground; it became established more slowly than *P. melanodon* and it never covered as much ground, but it continued to expand in cover up to the end of the monitoring period, while *P. melanodon* was decreasing.

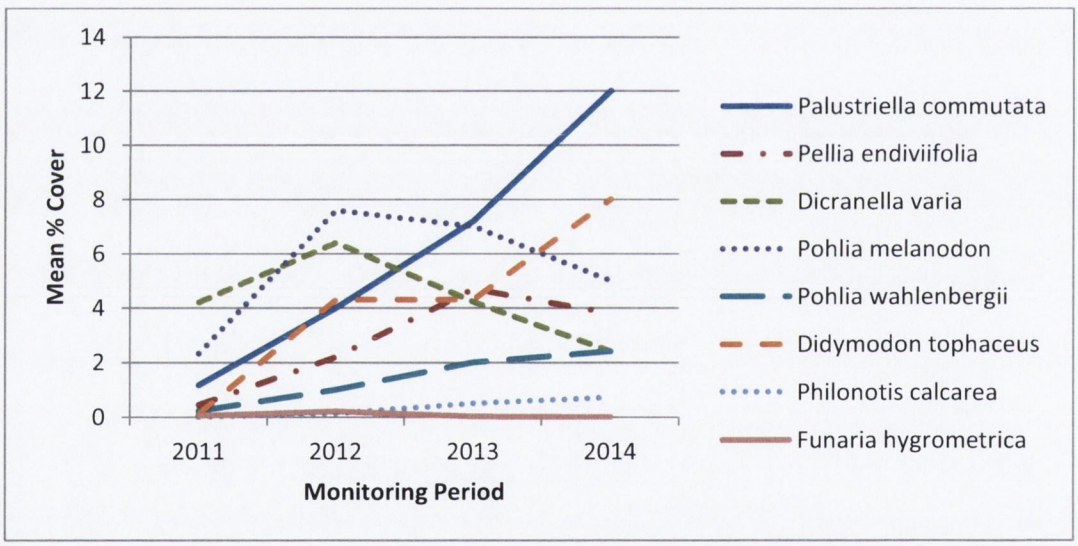


Fig. 7.4: Bryophyte species which colonised incipient tufa deposits following landslides. Mean % cover for five permanent quadrats.

Of the more characteristic petrifying spring species, *Palustriella commutata* was present in most permanent quadrats from early on, but in very small amounts. It expanded steadily from a mean cover of 1.2% in the first year to 12% by the end of the monitoring period (for example, Photos 7.23 and 7.24). *Pellia endiviifolia* was also frequent in the early stages of recolonisation, again in small quantities. It expanded more slowly than *P. commutata* and declined in three out of five quadrats during the third year. The typical habitat of *P. endiviifolia* is steep, shaded banks and it

[3] Data are for five permanent quadrats (PQs A – E) which survived for the entire monitoring period.

may have been unable to compete with other species on the unshaded, gentle slopes of the three permanent quadrats in which it declined (Table 7.10 below). At Glinsk, the steepest and most shaded location, *P. endiviifolia* continued to expand up to the end of the monitoring period (reaching 10% cover). *Didymodon tophaceus*, also typical of steep, shaded surfaces, formed a large colony at Glinsk, occupying 40% of the surface area by the end of the monitoring period (Photo 7.29). Elsewhere, it was absent or occupied only small areas (up to 1% cover). *Philonotis calcarea* was not recorded in the first year but it colonised most of the permanent quadrats during the monitoring period, up to a maximum cover value of 2%. *Eucladium verticillatum* was notably absent from permanent quadrats. A tiny fragment was recorded at Glinsk in the first year, but it was not refound. The mosses *Cratoneuron filicinum, Brachythecium rivulare, Bryum pseudotriquetrum, Platyhypnidium riparioides* and *Calliergonella cuspidata* were recorded intermittently in small quantities; their presence did not follow any discernible pattern from year to year.

Table 7.9: Most frequently occurring species in landslide permanent quadrats (PQ; n= 8), compared with relevés on stable ground (QLs) in the same spring complexes (n=27). 'Max Year' is the year with the highest mean cover for the five quadrats which survived all four years (PQs A – E; 2011= Year 0, 2014= Year 3).

Species	Frequency		Mean Cover		Max Year
	Landslide PQs	Stable QLs	Landslide PQs	Stable QLs	
Pohlia melanodon	100%	4%	4.7	<0.1	1
Palustriella commutata	100%	100%	4.6	32.1	3
Pellia endiviifolia	100%	67%	2.3	4.2	2
Dicranella varia	88%	7%	4.3	<0.1	1
Juncus articulatus	88%	30%	1.2	1.5	3
Pohlia wahlenbergii	88%	7%	1.1	<0.1	3
Agrostis stolonifera	75%	85%	3.1	3.9	1
Didymodon tophaceus	63%	26%	3.2	0.6	3
Carex flacca	63%	33%	2.7	3.2	3
Cratoneuron filicinum	63%	37%	1.1	1.1	3
Equisetum telmateia	63%	74%	0.5*	6.5	1
Brachypodium sylvaticum	63%	37%	0.2	1.3	2
Calliergonella cuspidata	63%	30%	0.2	3.8	3
Brachythecium rivulare	63%	67%	0.1	3.3	2

*barely above ground in March most years; underestimated compared to evergreen species.

The most frequently occurring vascular plants in the early stages of recolonisation were *Juncus articulatus, Agrostis stolonifera, Carex flacca* and *Equisetum telmateia* (Table 7.9 above). The abundance of these species was somewhat variable, in part due to seasonal factors. *Epilobium parviflorum* and *Tussilago farfara* were early colonisers of some landslide quadrats; the latter species in particular was striking in its ability to move in rapidly on bare ground.

Of the eight permanent quadrats set up at the start of the monitoring period, only five (PQs A – E) were still in situ for the final data collection period three years later. Two quadrats in Glenbarrow were lost due to a landslide during the second year of monitoring (Photos 7.25 and 7.26) and one at Glenasmole was lost in a landslide during the third year. All permanent quadrats were located within or adjacent to woodland but most were not shaded by overhead canopy as successive landslides had left large open clearings without canopy cover. One permanent quadrat at Glenasmole and one at Glenbarrow were lightly shaded by nearby trees (Table 7.10). The site at Glinsk was the only heavily shaded site.

Tufa formation proceeded rapidly on landslide sites during the monitoring period. When first surveyed in March 2011, tufa occupied 19% of the ground surface of quadrats. This increased to 49% after one year, 66% after two and to 85% of surface area by the end of the third year. Vegetation cover increased from 11% at the start of monitoring to 48% by the end (PQs A-E), while bare soil decreased from 59% to 1% in the same period.

Table 7.10: Characteristics of permanent quadrats on landslides. 'Years' is the duration of monitoring, beginning at Year 0 in March 2011. The range for tufa and vegetation cover is from the first to the last annual record.

PQ	Site	Tree Canopy	Slope	Years	Tufa Cover	Veg. Cover
A	Glenasmole	0%	30°	3	0 – 90%	5 – 30%
B	Glenasmole	25%	20°	3	95 – 100%	10 – 15%
C	Glenasmole	0%	20°	3	0 – 50%	15 – 65%
D	Glinsk	70%	80°	3	0 – 95%	1 – 78%
E	Glenbarrow	10%	30°	3	0 – 90%	25 – 50%
F	Glenbarrow	0%	30°	1	0%	1 – 5%
G	Glenbarrow	0%	30°	1	0%	1 – 5%
H	Glenasmole	0%	40°	2	20 – 80%	25 – 50%

Incipient tufa deposits did not fit clearly into the classification of tufa types (Pentecost & Viles 1994, Pentecost 1995, 2005; see Section 1.2.5). PQ B and H, both in Glenasmole, formed the most strongly consolidated tufa. Both were located on small streams and had already developed a substantial stream crust / cascade of tufa by the time monitoring began. In both cases, this contrasted sharply with the bare, loose soil in the surrounding seepages (Photo 7.30). Tufa continued to accumulate in PQ B during the course of the survey but flowing water limited the extent of colonization by plants (PQ H was lost in a subsequent landslide). Nearby quadrats located on unstable soil formed only a thin layer of unconsolidated tufa during the monitoring period (for example PQ C, Photos 7.23 and 7.24); in some cases, the instability of the soil surface militated against plant colonisation (for example PQ A, Photo 7.30). PQ D at Glinsk was steeper and shadier than the other permanent quadrats. In spite of the almost vertical incline, the surface was mostly stable over the course of monitoring and became vegetated with a fine turf of the small acrocarps coated in unconsolidated tufa.

The plastic markers used to measure growth rates also contributed some insights into species displacement. In seven instances, *Palustriella commutata* replaced other species during the monitoring period: *E. verticillatum* four times, *D. tophaceus* twice and *P. endiviifolia* once (Photos 7.17 and 7.18). *E. verticillatum* replaced *D. tophaceus* three times. While *D. tophaceus* displayed a greater ability for colonising newly formed tufa, *E. verticillatum* was the more abundant species in stable relevés (mean cover 3.8 times that of *D. tophaceus*).

7.3 Discussion

The mean rate of tufa deposition, 20.5mm/yr, is high compared to other studies. It is four times faster than the mean rate calculated in Pentecost's review (2005). It is 2.6 to 3.7 times faster than the mean rate reported in recent Spanish river studies (7.85mm/yr in the River Piedra and 5.51mm/yr in the River Añamaza; Arenas *et al.* 2014 and Auqué *et al.* 2014). These detailed, long-term studies found that the fastest rate occurred in association with cyanobacteria (up to 18.27mm/yr), while the Spanish facies most similar to the sites surveyed in this study – cascades with algae and bryophytes – accumulated at up to 8.32mm/yr, just 41% of the rate in this study.

For the most part, accumulation of tufa takes place in the presence of bryophytes; *Palustriella commutata,* in particular, is associated with rapid deposition. The presence of shallow water, well aerated as it tumbles over uneven surfaces, also promotes high rates of deposition. The interaction between these two factors, a dense moss weft on which tufa can accumulate and shallow, trickling spring water delivering the necessary ions as it filters through the moss shoots, combine to provide optimal conditions for deposition. Nitrate levels (up to 44mg/l, indicative of anthropogenic enrichment, Section 6.1.1) did not impede tufa formation but in fact had a positive effect on deposition rates; similar effects have been reported from Plitvice (Kepcija *et al.* 2011). This effect is greatest in the presence of *P. commutata* suggesting that nitrate promotes tufa deposition indirectly, by boosting the growth of species like *P. commutata* on which tufa can form. Elevated levels do, however, impact negatively on species richness (Section 5.2.4; Fig. 5.17). Unlike nitrate, alkalinity has greatest effect when surface water is more plentiful. High alkalinity levels alone do not guarantee that tufa will be deposited rapidly; the difference in deposition rates at nearby bars with the same alkalinity levels are likely to be due at least in part to difference in aeration levels.

While this study is mostly concerned with tufa deposited in association with bryophytes, the most rapid deposition rate (albeit in a small sample) was associated with the green filamentous alga *Vaucheria* sp. The capacity of this genus to contend with and/or promote rapid deposition was evident at a number of sites. The measured rate of tufa accumulation in association with *Vaucheria* of 136mm in seven months (beginning in August and thus having missed most of the summer when deposition is greatest, Arenas *et al.* 2014 and Auqué *et al.* 2014), exceeds the mean growth previously estimated for this genus, 14.7 mm/yr (Pentecost 2005), almost by a factor of 10. *Vaucheria* grows as fine filaments, aligned parallel to each other; it grows upwards or leans in the direction of the flow of the water. Tufa coats the filaments and forms fine-grained deposits,

reproducing the parallel patterning produced by the algal filaments; the measured rate represents both algal growth and the rate of tufa deposition.

The three-dimensional surfaces in tufa depositing systems and the erratic patterns of shifting deposition make data collection a challenging task. Tufa was seldom deposited in an even layer in the springs sampled in the present study. The measured rate of 20.5mm/yr is, in some respects, a conservative estimate, as some of the most rapidly accumulating samples were unmeasurable when they exceeded the height of the bars. Conversely however, measurements made perpendicular to a fixed bar give a somewhat distorted estimate of growth that is not perpendicular to the plane of measurement. Data on the most rapid accumulation rates are elusive due to the unpredictable manner in which pockets of deposition shift. As tufa builds up, it blocks the flow of spring water, causing it to divert laterally, following the route of least resistance. Rates of deposition fall off as tufa dries out, so that, while a mean accumulation rate offers a general estimate, in reality there is a continuum from rapid down to zero accumulation.

Tufa-depositing sites are therefore dynamic, not just in growing vertically, but in shifting laterally over time. Furthermore, tufa deposits are often translocated downslope, especially in situations like Glenasmole, Glenbarrow and Skerries, where the weight of the accumulated mass of tufa and the hydraulic effect of spring water issuing from unstable soils on steep hillsides make landslides an integral part of the natural sequence of change. This is compounded at some locations by the action of the tide or of rivers at the foot of the hill.

Anthropogenic factors were also at work at some of the sites surveyed. Agricultural practices in the environs of the bars at Skerries, Hartwell and Knocksink most likely caused the elevated nitrate levels. One bar at Skerries (Bar 15) was located below a pipe outfall draining the lands above. It gave rise to a somewhat atypical tufa cascade colonised by *Didymodon tophaceus* (Photo 7.2, see also Photos 5.3 and 5.4). It is worth noting that, in spite of the artificial channelling of water, tufa was still formed, but at a much lower rate and with fewer associated species than at Bar 14, located on the same stretch of coastline.

7.3.1 Species strategies

Apart from its ability to tolerate the extreme chemical conditions in petrifying springs, *Palustriella commutata* is one of the few species that can cope with the rapidly changing surface level resulting from the accumulation of tufa. While many other species would be inundated with tufa, the robust weft structure of *P. commutata* has the capacity to outgrow tufa deposition rates, attaining height gains of approximately 27.6mm/yr (e.g. Photos 7.3 and 7.4; 7.19 and 7.20). *Cratoneuron filicinum* also seems capable of outgrowing rapidly accumulating tufa, with height increases of up to 40mm/yr. The slower growth rates measured for the turf-forming acrocarps *Didymodon tophaceus* (9.1mm/yr) and *Eucladium verticillatum* (9.5mm/yr) indicate that they can contend only with the more slowly accumulating tufa deposits. Of these two species, *D. tophaceus* displayed a greater ability for colonising newly formed tufa, whereas *E. verticillatum* was more abundant on stable sites. *P. commutata* has the undisputed ability to displace both of these smaller acrocarps in stable conditions, though it was observed to be more prone to falling off vertical banks than the smaller acrocarps.

The results of this study are not directly comparable with those of Pentecost (1987b) – he measured shoot length, not height increase, and some data are seasonal, not annual – but insofar as comparisons can be made, my data suggest faster growth rates. In the case of *E. verticillatum*, with its upright acrocarpous shoots, Pentecost's shoot length increase of 3.9mm/yr (for a single sample) suggests a much slower growth rate than the height increase in this study (9.5mm/yr).

Dicranella varia and *Pohlia melanodon*, early colonisers of incipient deposits, seldom persist in mature stands on stable tufa. While they have the ability to disperse rapidly onto newly available surfaces, their small stature is not well suited to long term habitation of rapidly accumulating deposits or competing with the larger bryophytes characteristic of more stable deposits.

7.3.2 Plant Communities

Bars were installed prior to the collection of relevé data or the consideration of different plant communities. It is interesting to note that the vegetation at most bars belongs to just two communities, *Brachythecium rivulare – Platyhypnidium riparioides* Tufaceous Streams & Flushes, and *Palustriella commutata – Geranium robertianum* Springheads. Both are characterised by strongly forming tufa cascades and they presented opportunities for measuring actively depositing, solid tufa. The same is true to a lesser extent of *Palustriella commutata – Agrostis stolonifera* Springheads, the community to which one bar belongs, where tufa cascades are sometimes present. However, the group most strongly typified by massive cascade formation, *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades, is not represented in the bar locations. The steep slopes on which this community forms are poorly suited to installing bars.

The other communities not represented in the data on deposition rates are Groups 5 to 8, which seldom contain solid tufa. Tufa formation in these communities is more patchy, often consisting of paludal tufa or thin stream crusts. The poorly consolidated nature of the deposits makes them unsuitable for measuring by the methods used here. In addition, the exceptionally high conservation status of some locations, especially sites on the Benbulbin Range, make them unsuitable for the somewhat intrusive procedure of installing bars. The small amounts of tufa typically present in such communities suggest that deposition takes place at a much slower rate.

7.3.3 Methods

Tufa deposition is controlled by complex interactions of parameters which are not easily quantified. Microtopography plays a key role in determining aeration levels of spring water. Biotic factors, close to the sample point but not picked up at the precise location of the sample, may exert an influence that goes unrecorded. Much growth of tufa results from chance events – where debris happens to fall or become trapped, the resulting deflection and increased aeration of the spring water and the increased surface area on which precipitation can occur. A much larger sample would be necessary to explain such patterns adequately. Nevertheless, the data presented here provide an insight into some of the key factors.

Leaf litter, for example, provides surfaces on which tufa can be deposited (Emeis *et al.* 1987, Golubić *et al.* 2008) and thus it was investigated in this study as a possible factor influencing accumulation rate. However, in suitable conditions, leaf litter becomes coated with tufa very rapidly (Photo 7.12); in such cases, the rod made contact with tufa, not leaf litter, and therefore

the latter went unrecorded. Where leaf litter was recorded as being present, it was more likely to be fallen leaves resting above the influence of spring water, for example on top of moss stems.

The surface of tufa deposits is not sharply defined, especially where plants are present, as density of tufa decreases gradually moving upwards along the plant shoots. The method of allowing the resting position of the rod to determine the surface provides an objective means of defining the upper level of the tufa deposit. It results in unencrusted, fresh bryophyte growth being included in the surface measurement, but bryophytes are an integral part of the structure of many petrifying spring deposits, just as they are, for example, in peatlands. In this context, bars allow measurements of bryophyte-associated tufa deposition to be made in a less intrusive way than, for example, using limestone tablets which may take some time to acquire a bryophyte flora. The different methods – especially the lower level of disruption to the habitat – may in part explain the faster accumulation rate estimated in this study compared with the Spanish river studies.

The method used to measure bryophyte growth in this study gives an estimate of the height increase of the weft, turf or thallus, rather than a direct measure of shoot elongation. It is subject to erratic measurements, since the surface, especially of larger pleurocarp wefts, is uneven (hence some negative measurements). However, shoot growth, too, is erratic. Relocating marked shoots can be problematic and marking a shoot can interfere with growth. The variable estimates obtained by Pentecost (1987b) illustrate the challenges involved. Measuring growth rates of small acrocarps in the present study was somewhat more straightforward than measuring pleurocarps since the surface is more even.

Finding suitable sites for the installation of bars proved difficult; many actively accumulating deposits are too wide to be spanned by measuring bars without losing rigidity. Even at potentially suitable sites, finding secure anchorage for the bars took several attempts. Nevertheless, the fourteen bars for which measurements are presented remained in place without any signs of movement or interference from March 2011 to March 2013. Stainless steel is expensive, and the cost prohibited setting up more bars. However, it minimises potential reactivity with tufa precipitation processes and it functioned without rusting or otherwise deteriorating over the course of the study, allowing the rod to slide through the holes without resistance. The measurement process was time consuming and somewhat awkward, but it facilitated the making of measurements to the nearest millimetre in an objective and unambiguous manner. Making measurements entails a certain amount of trampling. This did not cause any noticeable damage to sites, but there is the potential for it to become destructive if repeated data collection visits are made. To minimise the impact of trampling on the samples being measured, all measurements

were made from below the bar rather than above it to avoid knocking debris onto the sample locations. Where there was more than one bar on a hillside, the lowest was measured first.

The surface within the permanent quadrats was often unstable and, being located on unstable hillsides, they were subject to disturbance from above as well as within. Erratic patterns recorded for some species may reflect this instability or may be due to omissions in recording, especially where species occurred as tiny fragments. The abundance of vascular plants was influenced by seasonal factors more than that of bryophytes. All records were made in March, but there was wide variation from year to year as to how far growth had advanced, depending on the conditions over the winter and early spring.

Numerous site visits were made to Glenasmole each year over the course of the study and a very rapid deposition rate was evident, but this is not reflected in the measurements (Fig 7.1, Table 7.3). There are a number of reasons for this. Firstly, where the most rapid deposition took place, tufa overtopped the bar and could not be measured (App. VI, Bar 8). Secondly, the flow of water shifted laterally so that deposition was not always occurring at the locations being measured. For example, the middle bar was bypassed by much of the stream water in the second year (Photo 7.11), although where water continued to flow beneath the bar accumulation was rapid (Photo 7.12). Thirdly, deposition is not evenly distributed along the hillside. It is fastest in the wide, shallow, well-aerated upper parts of the stream, where the middle and upper bars (Bars 7 and 8) eventually both became overtopped by tufa and where deposits are mostly too wide to be spanned by bars. It is slower below, where the water flows rapidly in a narrow v-shaped channel (Bar 6) and the erosive force of the flow rate militates against deposition.

In spite of initial concerns that the timeframe of the study might be too short to record deposition rates, the opposite was in fact found to be the case. At most locations, it was possible to make measurements over one or two years only; by the end of the third year most bars could not be measured. Those that were still in place and not overgrown by tufa or vegetation were all (except one) showing signs of drying out as water diverted.



Photo 7.1: Stainless steel box section bar clamped to angle irons. TB02 Coneyburrow Wood, Camcor River Valley, Slieve Bloom Mountains, March 2011



Photo 7.2: Making measurements: stainless steel rod, 6mm ø, 500mm long, lowered through hole in crossbar. The surface height was the level at which the rod rested under its own weight. The length of rod above the bar was measured to the nearest mm. TB15, Skerries, Co. Dublin, March 2011.



Photo 7.3: TB14 Skerries as installed, March 2011. Threaded bars were cemented into bedrock to secure the crossbar at this location.



Photo 7.4: TB14 Skerries, March 2013, with *P. commutata* growing over the bar. This was the bar with the most rapid deposition. Mean surface height increases of >50mm/yr were recorded at 8 holes with a maximum value of 81mm/year (averaged over two years). Pebbles thrown up by high tides lie on top of *P. commutata* (foreground).



Photo 7.5: TB14 Skerries, March 2014: The bar and part of the tufa cascade were swept away by winter storms.



Photo 7.6: TB14 Skerries, March 2014. Only the threaded bar remains, cemented into bedrock.



Photo 7.7: TB06 Glenasmole Lowest Bar – as installed in March 2011



Photo 7.8: TB06 Glenasmole Lowest Bar – March 2014. Barely changed. Fast flowing water militates against deposition of tufa.



Photo 7.9: TB08 Glenasmole Top Bar as installed, March 2011.



Photo 7.10: TB08 Glenasmole Top Bar overtopped by tufa, March 2013.



Photo 7.11: TB07 Glenasmole Middle Bar, March 2012. At the time of installation (March 2011), the bar spanned the entire stream. A year later, much of the flow had diverted around the bar



Photo 7.12: TB07 Glenasmole March 2012: Hole 23 recorded an increase of 68mm over 1 year. Leaf litter becomes incorporated in the rapidly forming tufa. Microbial films on the surface of the decaying leaves promote tufa deposition by trapping seed crystals (*e.g.* Golubić *et al.* 2008).



Photo 7.13: TB04 Glinsk (East) Lower Bar as installed, March 2011.



Photo 7.14: TB04 Glinsk (East) Lower Bar in March 2013 with *Juncus effusus* and *J. inflexus* encroaching from the edge.



Photo 7.15: TB11 Hartwell as installed, March 2011.



Photo 7.16: TB11 Hartwell in March 2012, overgrown with *Nasturtium officinale, Agrostis stolonifera* and *Holcus lanatus.*

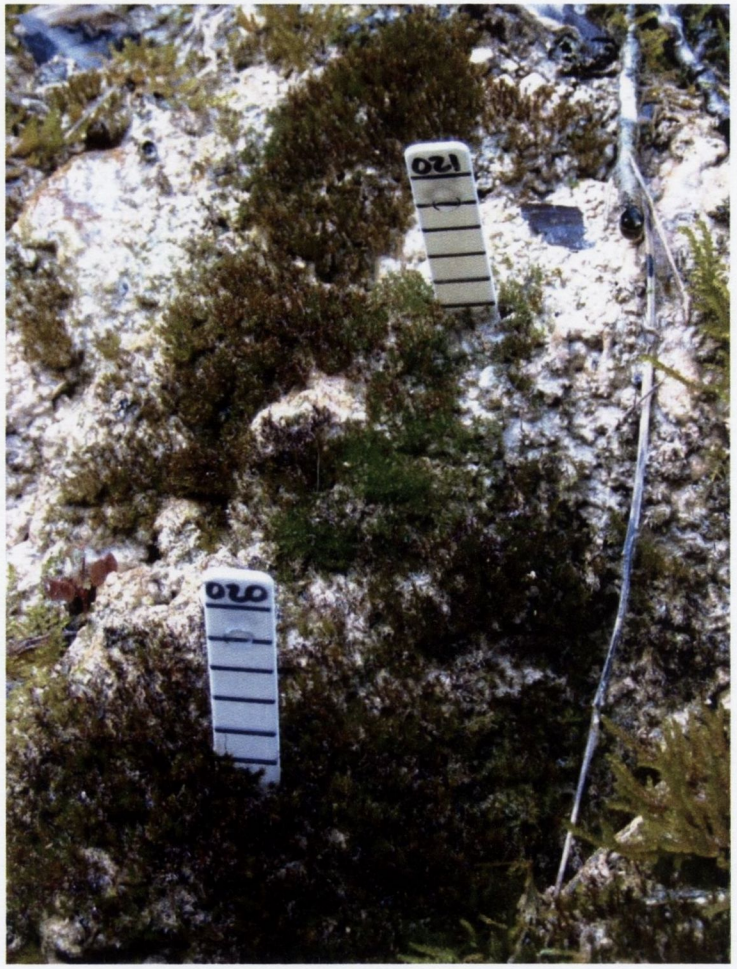


Photo 7.17: Plant labels (PL) in March 2011 to measure bryophyte growth rates at Glinsk. PL020 recorded a height increase of 10mm from March 2011 to March 2012 for *Didymodon tophaceus*. PL021 recorded 15mm growth for *Eucladium verticillatum* in the same period. Lines are 10mm apart.



Photo 7.18: Two years later (March 2013), both PL020 and PL021 had been overgrown by *Palustriella commutata*. (It can be seen encroaching from the right hand side in Photo 7.17.)



Photo 7.19: Ertalon rods in *Palustriella commutata* at Glinsk as installed, March 2011. Black rings are at 50mm intervals.



Photo 7.20: By March 2012, these rods had recorded increases of 23mm (closest rod), 24mm and 40mm (furthest rod) in the height of the weft.



Photo 7.21: Hartwell August 2011. Ertalon rods in tufa associated with the filamentous green alga, *Vaucheria* sp. Black lines are at 50mm intervals



Photo 7.22: Hartwell March 2012. Increase in surface height over a seven month period was 132mm at the rod on the left and 140mm at the one on the right.



Photo 7.23: PQC Glenasmole March 2011. Living vegetation occupies only 15% of surface area but contains 25 species; *Agrostis stolonifera* has highest cover value (5%). The most abundant bryophytes are *Palustriella commutata* (5%), *Pohlia melanodon* (5%) and *Dicranella varia* (1%).



Photo 7.24: PQC Glenasmole March 2014. Three years later, living vegetation covers 65% of surface area (16 species present). *P. commutata* occupies 35% of the surface, *D. varia* 2% and *P. melanodon* was not recorded. *Carex flacca, Agrostis stolonifera* and *Cratoneuron filicinum* cover 5% each.



Photo 7.25: PQF Glenabarrow March 2012: Seepage with incipient tufa formation on unstable hillside.



Photo 7.26: PQF Glenbarrow March 2013: aftermath of landslide in Winter 2012/13. Two permanent quadrats (PQF and PQG) were lost.



Photo 7.27: PQE Glenbarrow March 2012: early colonisation by *Pohlia melanodon* (30% cover) and *Dicranella varia* (20% cover) with smaller amounts of *P. wahlenbergii, Carex flacca, Juncus articulatus* and *Brachypodium sylvaticum*.

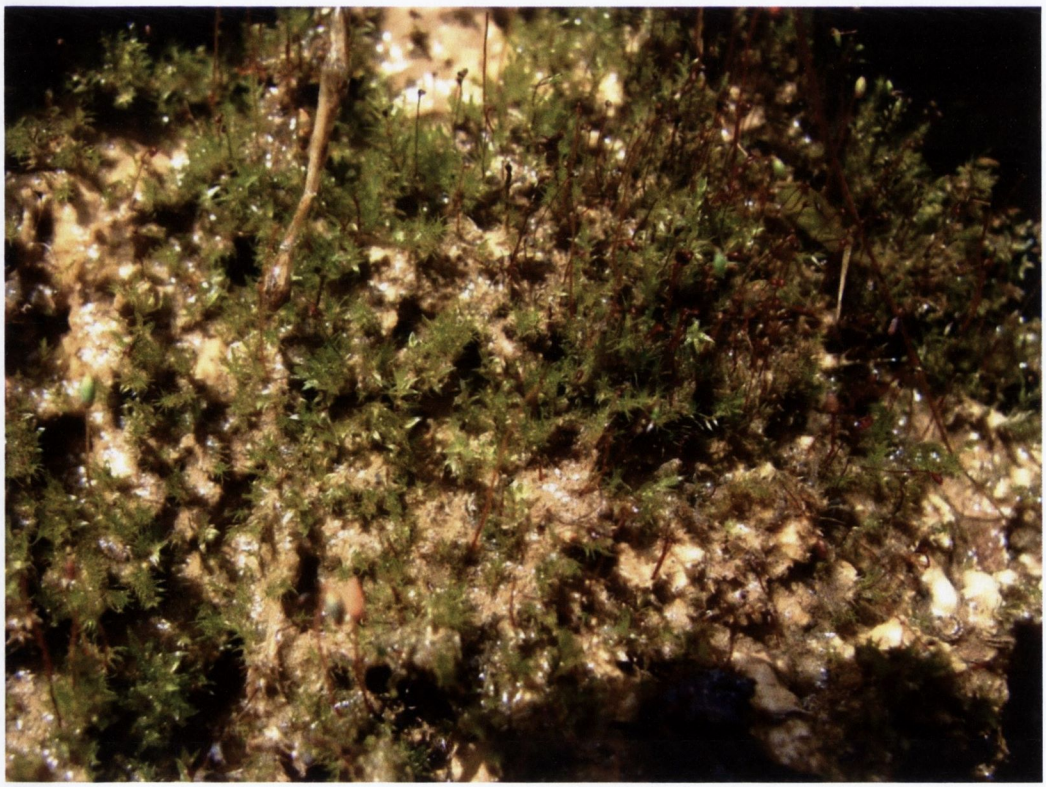


Photo 7.28: PQE Glenbarrow March 2013: incipient tufa formation with *Dicranella varia* (with red sporophytes) and *Pohlia melanodon* (scattered shoots). Both are early colonisers of freshly exposed seepages but they decline after the first few years.



Photo 7.29: PQD Glinsk March 2014. Steep face recently colonised by *Didymodon tophaceus, Pohlia melanodon* and *Pellia endiviifolia*. Older wefts of *Palustriella commutata* overhang from above.



Photo 7.30: PQB (foreground, left) at Glenasmole, March 2011, and PQA (background, right). Trickling water has already deposited consolidated tufa in PQB, while the steep slope and unstable surface of PQA lacks tufa or vegetation.

8. Conclusion

The concept of the petrifying spring habitat type is at once obvious and challenging to define. The bryophyte-dominated vegetation of typical examples is highly distinctive, yet there is considerable variation in floristic composition and it is difficult to determine the boundaries between this and other related vegetation types such as *Adiantion* communities and small-sedge fens. In the early phytosociological studies, the lack of character species for the alliance *Cratoneurion* was an indication of this dilemma; unusually for phytosociological entities, this one was defined in terms of its tufa-forming characteristics rather than by species (Koch 1928, Braun-Blanquet 1949). Tufa formation presents a useful diagnostic character, but this is not restricted to springs; it takes place equally profusely along streams and rivers as stream crusts, dams and waterfalls, and even persists in highly modified environments such as fountains and below pipe outfalls. Furthermore, ten very weakly tufa-forming samples (and two lacking tufa entirely) were distributed amongst five of the eight plant communities, rather than forming a distinct group themselves; the high group membership coefficients of most of these low-tufa samples showed they contained similar vegetation to the more strongly tufa-forming group members.

A summary of the eight Irish petrifying spring plant communities is contained in Fig. 8.1 below. At the top left, Group 1 *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades are massive cascade formations, dominated by bryophytes, occurring on the steepest slopes. Below this, in Fig. 8.1, are the woodland communities: Group 2 *Palustriella commutata-Geranium robertianum* Springheads, and Group 3 *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams and Flushes; both are on moderately steep slopes, with Group 3 frequently occuring downslope from Group 2. Located in the centre of the diagram are Group 4 *Palustriella commutata-Agrostis stolonifera* Springheads, which are intermediate in many respects between the other plant communities. This group contains unshaded spring heads (and some flushes) where *P. commutata* is dominant and is accompanied by graminoid species; it occurs on moderate slopes and is intermediate in species richness between the low species diversity groups to the left and the more species-rich groups to the right of the Figure. Groups 5, 6 and 7 are sedge-dominated communities on level or gently sloping ground; all are unshaded. Group 5 *Schoenus* Springs are dominated by *S. nigricans* with an underlayer of brown mosses; they typically contain well-consolidated, paludal tufa. Group 6 *Carex lepidocarpa* Small Sedge Springs are high in species diversity (second only to Group 8) but are only weakly tufa-forming. Group 7 *Palustriella falcata-Carex panicea* springs are characterised by bare stone (especially limestone pavement in the Burren) and often bare tufa (*e.g.* at the foot of the Benbulbin Range). Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs are montane communities containing a suite of rare bryophyte

species. They are mostly confined to the Benbulbin Range and west Fermanagh uplands, but are also represented in a slightly depauperate form in the Burren and on the coast of Co. Antrim.

All eight groups described are worthy of conservation. They contain highly specialised and ecologically distinctive plant communities and they occupy only a very small land area in total. Group 8 *Saxifraga aizoides-Seligeria oelandica* Springs are of the highest conservation value; the Irish populations of *Seligeria oelandica* are of significance on a world scale (Lockhart *et al.* 2012). Its co-occurrence with other rare bryophytes –*S. patula, Hymenostylium recurvirostrum* var. *insigne* and *Orthothecium rufescens* – makes this an exceptionally distinctive and important community.

Irish petrifying springs, broadly, conform to the *Cratoneuretum filicino-commutati* association (as per White & Doyle 1982); however, assigning them at this level fails to take into account the very great range of variation that occurs within the group as a whole. Group 1 comes close to *Adiantion* communities (*e.g.* Deil 1994) and the *Eucladietum verticillatum* Allorge bryophyte-dominated association of irrigated cliff faces (*e.g.* Philippi 1965). Groups 2 and 3 typically occur as small stands within drier woodland communities; they are related to the *Equiseto telmatejae-Fraxinetum* Oberd. ex Seib. 1987. Group 4 represent the unshaded, Atlantic facies of the *Cratoneuretum filicino-commutati* (Kuhn 1937) Oberd. 1977. The small-sedge communities of Groups 5, 6 and 7 are transitional to *Caricion davallianae* fens; they represent extreme calcicole sub-communities of the *Schoenetum nigricantis* (sensu Ó Críodáin & Doyle 1997) and the M10 *Pinguicula vulgaris-Carex dioica* Mires (Rodwell 1998b). The montane Group 8 with *Saxifraga aizoides* forms a distinct sub-community of the British *Saxifragetum aizoidis* McVean & Ratcliffe 1962; the rare bryophyte species of Group 8 are absent from the British community but they are a constant and characteristic feature of the Irish community as it occurs on the Benbulbin Range.

GROUP 1 n=18 SIL. WIDTH 0.20 (**HIGHEST**)

Eucladium verticillatum - Pellia endiviifolia Tufa Cascades

- **Steepest** slopes
- Highest **cascade** tufa cover; massive formations
- **Bryophyte**-dominated
- **Fewest** species (mean 9 species / relevé)
- Coastal and woodland cliffs
- Most **cohesive** group; small group

GROUP 2 n=26 SIL. WIDTH 0.16 (HIGH)

Palustriella commutata-Geranium robertianum Springheads

- Highest ***P. commutata*** cover (mean 61%)
- **Woodland** (mean tree canopy cover 51%)
- High **bryophyte** cover
- High **tufa cascade** cover; moderate slopes
- Springheads associated with next group:

GROUP 3 n=29 SIL. WIDTH -0.01 (**LOWEST**)

Brachythecium rivulare- Platyhypnidium riparioides Tufaceous Streams and flushes

- **Woodland** (mean tree canopy cover 50%)
- **Streams & flushes** forming below Group 2
- **Flowing water** is characteristic
- High **bare tufa** cover; **cascades** & **stream crust**
- **Incohesive** group – residuary (shaded flushes)

GROUP 4 n=28 SIL. WIDTH 0.04 (LOW)

Palustriella commutata- Agrostis stolonifera Springheads

- Central group; few distinguishing features
- Low cohesion; residuary
  - unshaded springheads (& flushes)
- High ***P. commutata*** cover
  - Unshaded equiv. of Gr. 2
- Accompanied by grasses
- Moderate slope, mixed tufa types

GROUP 8 n=13 SIL. WIDTH 0.17 (HIGH)

Saxifraga aizoides-Seligeria oelandica Springs

- **Rare bryophyte** species are characteristic
- **Species-rich**; (34 species/ relevé)
- **Weakly tufa** forming; with **stream crust** tufa
- **Montane; steep** slopes
- **Bare** tufa and bare ground plentiful
- **Cohesive** group

Groups 5 – 7 are **Sedge-dominated**
Mod/high species diversity
Level or gently sloping ground

GROUP 7 n=20 SIL. WIDTH 0.08 (MODERATE)

Palustriella falcata-Carex panicea Springs

- **Bare stone** plentiful (especially in Burren)
- **Stream crust** tufa, often bare

GROUP 6 n=30 SIL. WIDTH 0.9 (MODERATE)

Carex lepidocarpa Small Sedge Springs

- High **species diversity** (27 species / relevé)
- **Weakly tufaceous**; paludal tufa

GROUP 5 n=22 SIL. WIDTH 0.17 (HIGH)

Schoenus Springs

- *Schoenus nigricans* & **brown mosses**
- Crunchy **paludal** tufa and pools
- Highest cover by leaf litter / standing dead

Fig. 8.1: Summary of plant communities of Irish petrifying springs. 'Sil. width' = Silhouette width, a measure of how cohesive the group is.

The relationships of key environmental variables to the NMS ordination of plant communities are shown in Fig. 8.2 below. Axis 1 represents decreasing slope and, in tandem with this, decreasing cascade tufa; conversely, paludal tufa increases along Axis 1 as slope decreases. pH also decreases significantly along Axis 1. Axis 2 represents decreasing tree canopy cover and decreasing amounts of cascade tufa. Species diversity shows an inverse relationship to tree canopy cover and cascade tufa. Axis 3 is related to the nutrient status of spring water; phosphate concentrations increase along this axis. Thus, slope, tree canopy cover, phosphate concentrations and pH (in order of decreasing (absolute) r_s values) are very highly significant explanatory environmental variables of petrifying spring plant communities; tufa type (cascade or paludal) and species diversity are, in turn, influenced by these factors. Most woodland samples were located on hillsides (an anthropogenic artefact of lowland woodland clearance); hence, tufa cascades – which only form on sloping ground – show a similar pattern to tree canopy cover on Axis 2. All of the variables shown on Fig. 8.2 are significantly correlated with the ordination axes at $p<0.001$; other statistically significant variables not shown include dripping water, pools and trickling water (influenced by slope) , non-tufa, bare tufa, stream crust tufa, bare stone, leaf litter and altitude, all of which contribute to the characteristic ecology and physiognomy of individual plant communities.

Relationships among communities overlapping in species composition and influenced by many interacting environmental variables are complex. The scheme presented here reveals highly significant statistical relationships between the species-defined communities and a suite of individual abiotic factors. Groups 3 and 4 are the least cohesive groups; further sampling might reveal separate spring head and flush communities within Group 4 and might help to consolidate the central features of Group 3.

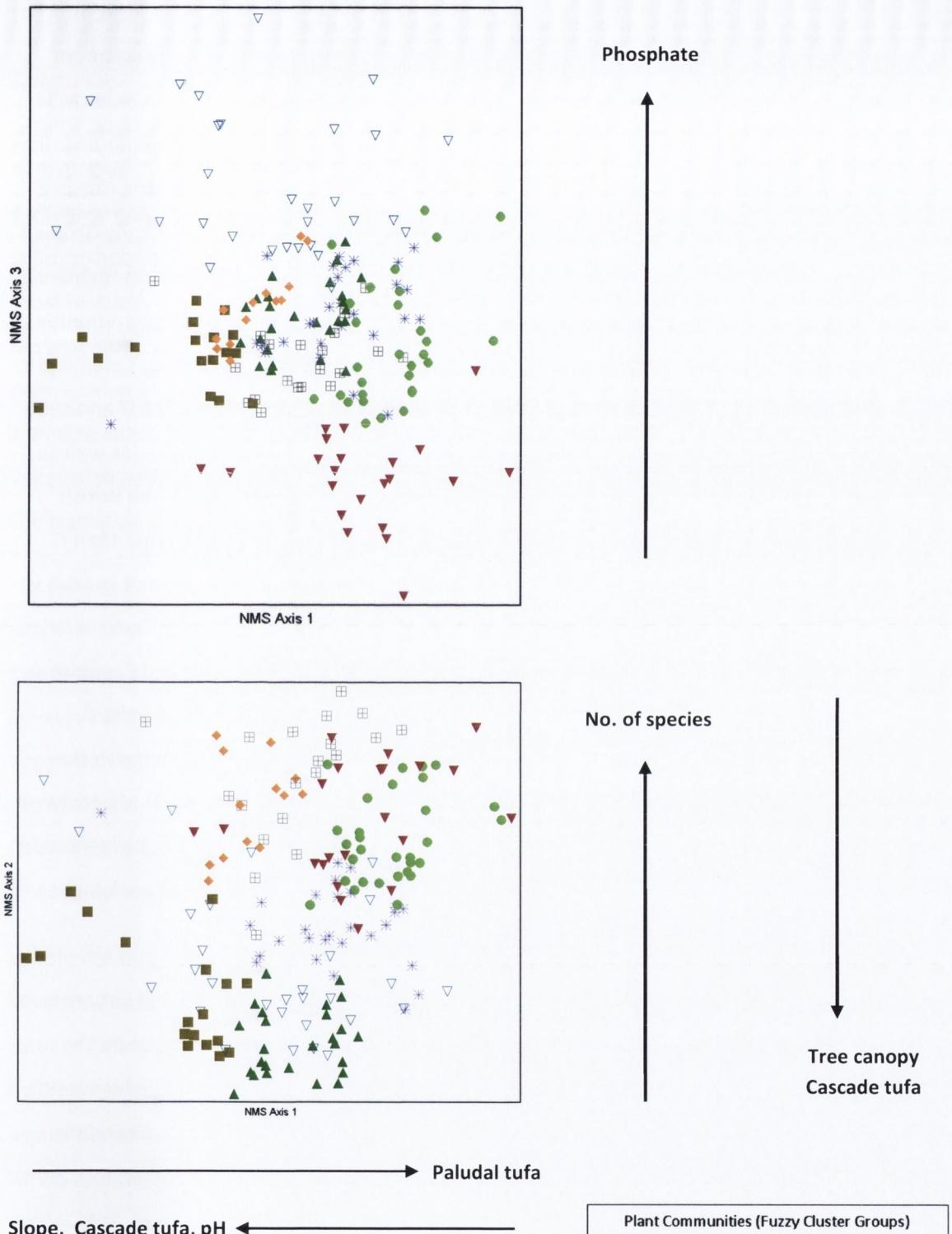


Fig. 8.2: NMS ordination showing plant communities and key environmental variables. ($|r_s| \geq 0.48$, $p<0.001$). (For other statistically significant variables see Figs. 3.16 and 5.9)

Irish petrifying spring communities lack clear affinities with British NVC communities. This is partly due to the fact that bryophytes are not comprehensively covered in that classification system; for example, *Palustriella falcata* is contained within *P. commutata s.l.*, and *Eucladium verticillatum* is not reported from any community. The NVC petrifying spring communities M37 *Cratoneuron commutatum-Festuca rubra* and M38 *Cratoneuron commutatum-Carex nigra* springs are montane in character and the former contains *Saxifraga aizoides*, but my montane Group 8 samples had few constant species in common with these two communities. Instead, my Group 8 samples had stronger affinities with *Saxifragetum aiziodis* communities of the Scottish Highlands (U15 *Saxifraga aizoides-Alchemilla glabra* Banks; my Table 4.8). The M37 and M38 communities are not strongly calcicole in their species composition – for example, the eponymous *Carex nigra* in the latter is indicative of only moderately base rich conditions (*e.g.* Jermy *et al.* 2007 and see also Section 5.2.4). There are other mismatches between these British communities (as well as synonymous communities; Table 2.4) and the floristic composition of my samples: the British studies frequently included *Festuca ovina* (rather than *F. rubra*), *Carex demissa* (rather than *C. lepidocarpa*) and *Philonotis fontana* (rather than *P. calcarea*). Of each pair, the former species is indicative of less calcicole conditions. In the present study, I very seldom recorded *Festuca ovina*, and I have no records for *C. demissa* or *P. fontana; Festuca rubra, C. lepidocarpa* and *P. calcarea* however, were frequent in my samples. Misidentifications may contribute (for example, *C. lepidocarpa* and *C. demissa* are variable in morphology and characters used to distinguish the species often overlap, Jermy *et al.* 2007). A recent study by Graham and Farr (2014) of petrifying springs in Wales reports both *Carex demissa* and *P. fontana* from weakly tufaceous, high-altitude sites; further sampling of upland habitats in Ireland is warranted, for example of Slieve League (e.g. Birks *et al.* 1969).

Epilobium alsinifolium, characteristic of petrifying spring habitats outside Ireland, but very rare in Ireland, was not recorded in any Irish petrifying spring samples. It was, however seen on the Benbulbin Range, above Glenade (Photo 8.1 below). Here, it grows on a damp cliff, which is not tufa-forming, in the shade of an ash tree; associated species were *Crepis paludosa*, *Geranium robertianum, Hymenostylium recurvirostrum* var. *insigne, Cratoneuron filicinum* and *Jungermannia atrovirens*. There was no trace of tufa amongst the vegetation.

Woodland springs have been poorly represented in published communities, for example in the NVC, although they have been recorded in Ireland and referred to the *Equiseto telmatejae-Fraxinetum* Oberd. ex Seib. 1987 (Kelly & Iremonger 1997, Cross & Kelly 2003). The general lack of description is, in part, a question of scale – springs are small local features in otherwise drier woodland communities. No trees (apart from some tree seedlings) were rooted in my woodland relevés, so my samples show only weak affinities with other woodland communities. The $4m^2$

relevé size used is appropriate for localised spring communities, but it doesn't take into account the surrounding ground on which the woodland canopy trees are rooted.

Due to their small spatial extent, petrifying springs frequently occur within a mosaic of related habitat types and delimiting one from the other is not straightforward; for example, petrifying springs grade into alkaline fen, both in the abstract floristic sense and in the concrete sense along ecological gradients within sites. In respect of Habitats Directive categories, 'the pragmatic solution adopted to the problem of overlapping habitats is to assign the stand in question to the most restrictive definition' (Evans 2006). I adopted this strategy in collecting data during the present study with regard to tufa-forming springs located within fens; the highly calcicole species composition of such samples, confirmed by high pH, alkalinity and calcium values of water samples, subsequently showed that these springs are markedly different from the broader vegetation and water composition of fens in general (Chapters 4 and 5). These samples represent the transition between petrifying springs in the strict sense and *Caricion davallianae* fens.

Nutrient enrichment of groundwater poses a serious potential threat to the conservation status of petrifying spring habitats; species diversity is significantly lower where levels of nitrates and phosphates are elevated. Any alteration, however slight, to the water composition of the high conservation value sites on the Benbulbin Range is likely to be detrimental to the species-rich vegetation and could bring about an irreversible loss of rare bryophyte species. Similarly, many of the characteristic species of small sedge communities are shown in this study to occur at low nutrient levels; increased concentrations of macronutrients are likely to be detrimental to these already threatened and declining habitats.

Within the range of spring waters sampled, increased nitrate levels are associated with increased cover by *Palustriella commutata* – coupled with a reduction in species richness – and increased rates of tufa accumulation. In high phosphate concentrations, however, *P. commutata* is replaced by *Platyhypnidium riparioides, Brachythecium rivulare, Cratoneuron filicinum* and filamentous algae. Steps need to be taken to reduce pollution levels at several sites; the local authorities, NPWS and the EPA have become involved locally where the worst levels of pollution were detected (South Co. Dublin and Co. Wicklow).

Undergrazing and overgrazing are both potentially damaging to the conservation status of petrifying springs. Further research is necessary to determine appropriate grazing levels; these will vary depending on factors such as plant community and landscape setting; for example, the sedge-dominated communities at Pollardstown Fen require some grazing to maintain species richness but the rare bryophyte habitats of the Benbulbin Range are vulnerable to poaching and overgrazing.

Removal and diversion of ground waters and spring waters also pose threats to petrifying spring habitats. Long-term monitoring of flow rates would assist in understanding and ensuring the conservation of important petrifying spring sites. Physical damage, landfill operations, illegal dumping, recreational activities, non-native species and inappropriate siting of conifer plantations all pose threats to petrifying spring communities; ongoing monitoring, with intervention where appropriate, is necessary to conserve these habitats.

Tufa accumulation is often very rapid and capable of overgrowing smaller, slower-growing acrocarps. Active Irish tufa cascades increase in height at the rate of 2cm per year on average, but reach rates in excess of 13cm per year locally. The more rapid rates of deposition of tufa measured in this study than reported elsewhere may (at least in part) be due to the different methods by which measurements were made. To date, the method of measuring from bars mounted above deposits is unknown elsewhere; it is less disruptive to habitats than other methods currently in use, but it is expensive, time-consuming and suitable in only a limited range of landscape settings. Further measurements of tufa accumulation rates and bryophyte growth rates would contribute to understanding the processes involved in present day habitats and also in interpreting palaeoenvironmental records in ancient deposits. Methods of measuring tufa accumulation rates need to be tested against each other so that results can be standardised and compared.

The algae of petrifying springs in Ireland are poorly recorded. Preliminary findings during the present study suggest that they are of interest and warrant further study.



Photo 8.1: *Epilobium alsinifolium* (two stems indicated by long arrows), a very rare plant in Ireland, on a cliff in the Benbulbin Range (above Glenade). It is growing with *Crepis paludosa, Geranium robertianum, Hymenostylium recurvirostrum* var. *insigne, Cratoneuron filicinum* and *Jungermannia atrovirens*, August 2014.

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Appendices

Appendix I	Site List by County / Region
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Site Ref.	Name	County/Region	VC	Grid Ref.	SAC	Relevés	Water Samples	Bars	Note
PS116	Murlough Bay	Antrim	H39	ID 19 41	-	QL208-QL212			Springs, streams and flushes
PS117	Marconi's Cottage	Antrim	H39	ID 15 41	-	QL210			Springs and flushes
PS041.1	Inis Meáin	Aran Islands	H9	IL 93 03	IE 0212	QL014			Spring, flush, seepage over coastal cliffs
PS041.2	Inis Meáin	Aran Islands	H9	IL 92 02	IE 0212				Seepage on coastal rocks
PS038	Glencar Waterfall	Benbulbin Range	H29	IG 76 43	IE 0623 QI	QL194, QL195			Waterfall, springs and seepages
PS040.1	Eagle's Rock (Lwr slopes)	Benbulbin Range	H29	IG 77 49	IE 0623 QI	QL198, QL199			Springs, streams and flushes
PS040.2	Eagle's Rock (Lwr slopes)	Benbulbin Range	H29	IG 77 48	IE 0623 QI	QL200			Springs, streams and flushes
PS058.1	Gleniff (Annacoona)	Benbulbin Range	H28	IG 72 46	IE 0623 QI	QL133, QL134			Springs, streams and flushes (private)
PS058.2	Gleniff (Annacoona)	Benbulbin Range	H28	IG 73 46	IE 0623 QI	QL127-QL129			Springs, streams, flushes, waterfall (private)
PS106	Cormac Reagh's Hole	Benbulbin Range	H28	IG 76 51	IE 0623 QI	QL130-QL132			Springs, streams and flushes (private)
PS107	Benbulbin Corrie	Benbulbin Range	H28	IG 70 45	IE 0623 QI	QL135			Springs, streams and flushes
PS108	Benwiskin	Benbulbin Range	H28	IG 71 48	IE 0623 QI	QL136			Springs, streams and flushes (private)
PS113	Eagle's Rock	Benbulbin Range	H29	IG 77 49	IE 0623 QI	QL196			Springs and seepage over cliffs
PS115	Larganavaddoge	Benbulbin Range	H29	IG 77 49	IE 0623 QI	QL197			Springs and seepage over cliffs
PS049.1	Feenagh	Burren	H9	IM 18 07	-	QL015	WS038		Karst springs and flushes (private)
PS049.2	Lismacsheedy	Burren	H9	IM 19 06	IE 0020 QI				Karst springs and flushes (private)
PS050	Ballyconry	Burren	H9	IM 20 07	IE 0020 QI				Spring from cave, piped to tanks (private)
PS052	Eanty More	Burren	H9	IM 25 00	IE 0054 QI				Karst springs and flushes (private)
PS053	Doomore	Burren	H9	IM 31 02	IE 1926 QI				Karst spring beside road
PS054.1	Keelhilla Nature Reserve	Burren	H9	IM 33 03	IE 1926 QI	QL071, QL072	WS045		Springs, fen and flush
PS054.2	Keelhilla Nature Reserve	Burren	H9	IM 33 04	IE 1926 QI	QL070			Waterfall

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Site Ref.	Name	County/Region	VC	Grid Ref.	SAC	Relevés	Water Samples	Bars	Note
PS083	Black Head, Tobernaliche	Burren	H9	IM 15 11	IE 0020 QI				Karst springs and flushes (private)
PS084	Black Head, Aghaglinny N	Burren	H9	IM 17 10	IE 0020 QI	QL027, QL028, QL090	WS041, WS042 WS043		Karst springs, flushes and waterfall (private)
PS085	Caher River, Fanore	Burren	H9	IM 14 09	IE 0020 QI		WS044		Seepages; falls on river
PS088	Aillwee Cave	Burren	H9	IM 23 04	IE 0054 QI				Speleothems; some bryophytes at lights
PS092	Glennamanagh	Burren	H9	IM 26 07	IE 0054 QI	QL074, QL075, QL140	WS036, WS037		Karst springs and flushes (private)
PS093	Cappanawalla, Newtown	Burren	H9	IM 21 06	IE 0020 QI	QL065, QL066, QL073	WS039, WS040		Karst springs and flushes (private)
PS094	Ballycahill Rises	Burren	H9	IM 24 04	IE 0054 QI				Karst spring and stream (private)
PS095.1	Teeskagh	Burren	H9	IR 28 96	IE 1926 QI				Karst springs, stream, waterfalls (private)
PS095.2	Teeskagh	Burren	H9	IR 29 96	IE 1926 QI				Springhead and flush (private)
PS100	Acres Village	Burren	H9	IM 25 07	IE 0054 QI	QL076			Karst springs and flushes (private)
PS103	Rinnamona L. Spring	Burren	H9	IR 29 94	IE 1926 QI	QL087	WS035		Spring head, stream and flush (private)
PS104	Rinnamona L. Fen	Burren	H9	IR 29 94	IE 1926 QI	QL088	WS034		Springs and fen (private)
PS051.1	Lisdoonvarna Spa	Clare	H9	IR 13 98	-				Cliff with seepage along stream (private)
PS051.2	Lisdoonvarna Park	Clare	H9	IR 12 98	-				Seepage and stream
PS099.1	Spanish Point	Clare	H9	IR 03 77	IE 1021 QI	QL050-QL052	WS033		Coastal springs and seepages
PS099.2	Spanish Point	Clare	H9	IR 03 78	IE 1021 QI	QL139	WS032		Coastal springs and seepages
PS090	Ballytrasna	Cork	H5	IW 97 63	-				Stream and coastal cascades
PS105	Ballybannan ASSI	Down	H38	IJ 37 35	-	QL124			Springs and fen (private)
PS014.1	Glenasmole Upr Reservoir	Dublin	H21	IO 09 21	IE 1209 QI				Springs/streams in pasture and hedgerows
PS014.2	Glenasmole Upr Reservoir	Dublin	H21	IO 09 22	IE 1209 QI	QL049	WS056		Tufa cascade; shady hedgerow / stream head

Site Ref.	Name	County/Region	VC	Grid Ref.	SAC	Relevés	Water Samples	Bars	Note
PS015.1	Glenasmole Lwr Reservoir	Dublin	H21	IO 09 22	IE 1209 QI	QL013, QL037, QL048 QL150-QL152, QL187-QL190, PQA, PQB, PQC, PQH	WS002, WS004 WS053-WS055 WS071	TB06 TB07 TB08	Woodland springs, streams and flushes
PS015.2	Glenasmole Lwr Reservoir	Dublin	H21	IO 09 23	IE 1209 QI	QL004-QL006, QL011 QL061-QL064, QL098	WS006, WS052		Woodland springs, streams, flushes
PS018.1	Fonthill	Dublin	H21	IO 07 35	-	QL158			Old ditch with tufa formation (private)
PS018.2	Fonthill	Dublin	H21	IO 06 35	-	QL156, QL157	WS137, WS138		Stream, seepage, tufa dams (private)
PS020	Balscadden Road	Dublin	H21	IO 29 39	-				Roadside spring
PS021	Kilrock Quarry	Dublin	H21	IO 29 38	IE 0202	QL165, QL166	WS134, WS135		Seepage and flushes
PS022.1	Coast N of Skerries	Dublin	H21	IO 22 61	-	QL153-QL155	WS046-WS048	TB14 TB15	Coastal tufa cascades and seepages
PS022.2	Balbriggan Coast	Dublin	H21	IO 21 63	-				Coastal tufa cascades and seepages
PS031	Kilternan Quarry	Dublin	H21	IO 21 21	-				Calcareous seepage (private)
PS048	Howth (off Upr Cliff Rd)	Dublin	H21	IO 29 38	IE 0202	QL084	WS136		Hollow with seepage
PS076	Balscadden Beach	Dublin	H21	IO 28 39	IE 0202	QL083	WS133		Coastal seepage
PS087	Portmarnock Martello T.	Dublin	H21	IO 24 44	IE 0205				Coastal seepage
PS102	Redrock	Dublin	H21	IO 26 37	IE 0202				Coastal seepage
PS109	Woodlands	Dublin	H21	IO 05 37	-	QL159	WS139		Tufa cascades, dams, waterfalls (private)
PS101	Kilgarrow	Fermanagh	H33	IH 07 51	UK30300 QI	QL081, QL082, QL217			Springs, streams and flushes (private)
PS111	Glencreawan Lough	Fermanagh	H33	IH 02 56	-	QL171			Springs, streams and flushes
PS119	Magho Cliffs	Fermanagh	H33	IH 04 57	-	QL218			Springs and seepage over cliffs (private)
PS063	Knocknagur	Galway	H16	IL 93 52	IE 2008	QL137			Springs, seepages and flushes (private)

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Site Ref.	Name	County/Region	VC	Grid Ref.	SAC	Relevés	Water Samples	Bars	Note
PS075.1	Slyne Head, Mannin Beg	Galway	H16	IL 58 46	IE 2074				Seepages and flushes
PS075.2	Slyne Head, Mannin Beg	Galway	H16	IL 60 46	IE 2074				Seepages and flushes
PS001	Louisa Bridge	Kildare	H19	IN 99 36	IE 1398 QI	QL031, QL122, QL123 QL179, QL180	WS013-WS015		Springs, pools and flushes
PS004.1	Pollardstown Fen SE	Kildare	H19	IN 77 15	IE 0396 QI	QL207	WS117		Paludal tufa east of public car park
PS004.2	Pollardstown Fen N	Kildare	H19	IN 76 16	IE 0396 QI	QL032, QL033, QL206	WS113-WS115		Fen with springs (private)
PS004.3	Pollardstown Fen SW	Kildare	H19	IN 76 15	IE 0396 QI	QL204, QL205	WS116		Fen with springs (private)
PS010	Grand Canal, Naas	Kildare	H19	IN 88 20	-				Tufa formations on canal gates
PS016	Ballynafagh	Kildare	H19	IN 81 29	IE 1387	QL085, QL086	WS123		Fen with springs
PS043	Kilcullen Valley Park	Kildare	H19	IN 84 09	-				Hillside seepages
PS044	Kingsbog	Kildare	H19	IN 71 08	-	QL019	WS112		Fen with springs (private)
PS045.1	Hartwell Upr	Kildare	H19	IN 94 21	-	QL172-QL175	WS007, WS008	TB10 TB11	Tufa cascade, stream, seepages (private)
PS045.2	Hartwell Upr	Kildare	H19	IN 94 20	-	QL099-QL101	WS118, WS119		Springs, seepages and fen (private)
PS046.1	Hartwell Lwr	Kildare	H19	IN 95 22	-	QL018, QL102, QL103	WS011		Tufaceous seepage in old drains (private)
PS046.2	Hartwell Lwr	Kildare	H19	IN 95 21	-				Tufaceous seepage in old drains (private)
PS055	Seven Springs	Kildare	H19	IN 91 17	-	QL077-QL079	WS059, WS060		Springs, seepages, flush and fen (private)
PS097	Monasterevin Aquaduct	Kildare	H19	IN 62 10	IE 2162 QI				Seepage from Grand Canal
PS047	Dysart	Kilkenny	H11	IS 59 39	IE 2162 QI	QL038	WS110		Tufa cascade (private)
PS066	Knocktopher Commons	Kilkenny	H11	IS 51 38	-				Springs and flush (private)
PS067	Dinin River, Muckalee	Kilkenny	H11	IS 55 69	-				Springs and flushes (private)
PS096.1	Thomastown Quarry	Kilkenny	H11	IS 58 43	IE 2252 QI	QL168, QL169			Springs, pools, fen, flush (private)
PS096.2	Thomastown Quarry	Kilkenny	H11	IS 58 42	IE 2252 QI	QL170			Springs, pools, fen, flush (private)

Site Ref.	Name	County/Region	VC	Grid Ref.	SAC	Relevés	Water Samples	Bars	Note
PS110	Kiltown, Castlecomer	Kilkenny	H11	IS 51 74	-	QL167	WS111		Spring, stream and flush (private)
PS062	Great Heath of Portlaoise	Laois	H14	IN 53 01	-				Springs and flush
PS086	Clonaslee, Coolagh	Laois	H14	IN 27 12	IE 0859	QL149			Springs and flushes (private)
PS039	Moneyduff Wood	Leitrim	H29	IG 79 34	IE 1976	QL191-QL193			Spring, stream and flush (private)
PS114	Arroo Mt (N cliffs)	Leitrim	H29	IG 82 52	IE 1403 QI	QL201-QL203			Springs, streams and flushes (private)
PS017	Carlingford Marina	Louth	H31	IJ 18 12	-	QL160	WS130		Roadside seepage
PS118.1	Rathcor W	Louth	H31	IJ 18 04	-	QL214, QL215			Coastal tufa cascades and seepages
PS118.2	Rathcor E	Louth	H31	IJ 19 04	-	QL213			Coastal tufa cascades and seepages
PS023	Marl Lough	Mayo	H26	IG 34 04	-				Large inactive deposits; small active spring
PS024	Castleburke	Mayo	H26	IM 16 77	IE 1774				Calcareous lake margin (private)
PS025	Old Head	Mayo	H27	IL 83 82	-	QL138	WS031		Coastal spring
PS026	Fallduff Strand	Mayo	H27	IL 83 82	-				Seepages
PS027.1	Dooaghtry Coast	Mayo	H27	IL 75 68	IE 1932 QI				Coastal springs
PS027.2	Dooaghtry Coast	Mayo	H27	IL 74 68	IE 1932 QI				Coastal springs
PS028	Dooaghtry Flush	Mayo	H27	IL 74 68	IE 1932 QI	QL093, QL094	WS029, WS030		Flushed dune slack
PS029	Crossmolina, Cloonamine	Mayo	H27	IG 14 15	IE 2298 QI				Calcareous seepage (private)
PS030	Eskeragh	Mayo	H27	IG 05 18	IE 1922	QL095-QL097	WS027, WS028		Springs with paludal tufa (private)
PS065	Ballycurrin Fen, Glasvally	Mayo	H26	IM 20 49	-	QL016, QL017, QL091 QL092			Fen with springs and pools
PS032	Broadboyne Bridge	Meath	H22	IN 91 70	-	QL021-QL023	WS127		Tufa cascade, seepages, flush (private)
PS033	Ardsallagh	Meath	H22	IN 88 62	-				Drains with calcareous seepage (private)
PS077	Kilcock, Knocknatulla	Meath	H22	IN 88 40	-	QL020			Calcareous seepage (private)

Appendix I: Site List by County / Region

Site Ref.	Name	County/Region	VC	Grid Ref.	SAC	Relevés	Water Samples	Bars	Note
PS098.1	Gormanstown Coast	Meath	H22	IO 17 68	-				Coastal tufa cascades and seepages
PS098.2	Gormanstown Coast	Meath	H22	IO 17 67	-				Coastal tufa cascades and seepages
PS098.3	Gormanstown Coast	Meath	H22	IO 18 66	-				Coastal tufa cascades and seepages
PS078	Lisduff Fen	Offaly	H18	IN 08 00	IE 2147 QI	QL176-QL178	WS086, WS087		Fen and springs (private)
PS080	Millpark	Offaly	H18	IS 11 91	-				Stream with tufa
PS081	Shannon Harbour	Offaly	H18	IN 02 17	IE 0216	QL024			Calcareous seepage (private)
PS007	Ridge of Capard	Slieve Bloom	H14	IN 36 07	-				Tufa cascade alongside forest track
PS008	Camcor River Valley	Slieve Bloom	H18	IN 21 04	IE 0412	QL181-QL184	WS061, WS062	TB03 TB04 TB05	Springs and flushes
PS012	County River	Slieve Bloom	H14/18	IN 24 08	-	QL067, QL068			Springs, seepages and flushes (private)
PS013	Silver River	Slieve Bloom	H18	IN 23 07	-	QL219	WS088, WS089		Tufa cascades on river banks
PS068	R. Barrow, Mill Quarter	Slieve Bloom	H14	IN 36 09	-	QL069			Seepage along river bank
PS069	R. Barrow, Mill Quarter	Slieve Bloom	H14	IN 36 08	-				Seepage and flush
PS070	Glenbarrow	Slieve Bloom	H14	IN 36 07	-	QL148, PQE, PQF, PQG	WS090		Seepages, flush, landslides
PS072	Ahagurty, east of Bridge	Slieve Bloom	H18	IN 17 00	-				Tufa cascades, seepages, flushes (private)
PS073	Coneyburrow Wood	Slieve Bloom	H18	IN 20 05	-	QL057, QL058	WS063, WS064	TB01 TB02	Tufa cascades, seepages and flushes
PS074	Glinsk Grove, Camcor R.	Slieve Bloom	H18	IN 21 04	IE 0412	QL059, QL060, PQD	WS065		Stream with seepages
PS082	Camcor River (S of river)	Slieve Bloom	H18	IN 21 04	-	QL025, QL026			Seepages and flushes (private)
PS112	Camcor River, Glenregan	Slieve Bloom	H18	IN 20 04	-	QL185, QL186	WS084, WS085		Springs, seepages and flushes
PS036	Ballincar	Sligo	H28	IG 66 38	IE 0627 QI	QL108			Coastal tufa cascades and seepage
PS056	Knocknarea	Sligo	H28	IG 63 34	-				Springs and seepage

Site Ref.	Name	County/Region	VC	Grid Ref.	SAC	Relevés	Water Samples	Bars	Note
PS037	Tully (Co. Council Yard)	Sligo	H28	IG 68 40	-				Tufa-forming pipe outfall
PS057.1	Knocknarea Glen W	Sligo	H28	IG 62 33	-	QL125			Springs and seepage over cliffs
PS057.2	Knocknarea Glen E	Sligo	H28	IG 63 33	-	QL126			Springs and seepage over cliffs
PS059	Slieveward, Corhawnagh	Sligo	H28	IG 66 28	-	QL104-QL107			Springs and fen (private)
PS060	Carrowgarry, Beltra	Sligo	H28	IG 59 31	-				Old drains with tufa (private)
PS061	Faughalstown	Westmeath	H23	IN 44 65	-	QL161-QL164			Springs and fen (private)
PS002.1	Knocksink Wood	Wicklow	H20	IO 21 17	IE 0725 QI	QL029, QL030	WS057	TB12 TB13	Woodland springs, streams, flushes
PS002.2	Knocksink 'Bog Meadow'	Wicklow	H20	IO 22 17	IE 0725 QI	QL040	WS058		Tufa cascade
PS003	Ballyman Glen	Wicklow	H20	IO 22 18	IE 0713 QI	QL080, QL119-QL121 QL141	WS066, WS067		Fen with springs (private)
PS005	Knockree (An Óige)	Wicklow	H20	IO 19 14	-	QL053-QL056	WS078-WS080		Springs and flushes (private)
PS006	East of Knockree	Wicklow	H20	IO 19 16	-				Tufa-forming flush (private)
PS071.1	Powerscourt Estate	Wicklow	H20	IO 20 15	-				Woodland springs, flush (private)
PS071.2	Powerscourt Estate	Wicklow	H20	IO 21 16	-				Fountains in Japanese Gardens
PS089	Cookstown, R117 at Arch	Wicklow	H20	IO 23 17	-				Seepage and flush (private)
PS091.1	Ardmore Pt (South)	Wicklow	H20	IT 32 87	IE 1766 QI	QL034	WS083		Coastal springs and seepages
PS091.2	Ardmore Pt (North)	Wicklow	H20	IT 33 87	IE 1766 QI	QL035, QL036	WS082		Coastal springs and seepages
PS091.3	Ardmore Pt (North)	Wicklow	H20	IT 33 88	IE 1766 QI	QL216	WS081		Coastal springs and seepages

Note: 'Private' denotes sites where access must be requested from the landowner; sites not marked private are not necessarily open to the public.
QI: Qualifying Interest (*i.e.* petrifying springs were a Qualifying Interest in the designation of the SAC)

Group 1: *Eucladium verticillatum-Pellia endiviifolia* Tufa Cascades

18 Samples (n)

0.20 Silhouette width

Relevé	Site	Name	MC	Alt.	Slope	Coast	Spp.	Can.	Casc.	Pal.	P. St.	NonT.	Flow.
QL013	PS015	Glenasmole D	100	214	70	-	13	20	80	0	-	20	40
QL028	PS084	Black Head B	62	59	36	<1km	21	0	90	0	-	5	93
QL034	PS091	Ardmore Pt A	77	5	25	C.S.Z.	9	0	20	0	-	20	64
QL038	PS047	Dysart	98	32	75	-	10	80	97	0	-	2.5	0
QL049	PS014	Glenasmole Upr	79	198	80	-	5	90	100	0	-	0	25
QL050	PS099	Spanish Pt A3	97	0	75	C.S.Z.	3	0	100	0	-	0	5
QL051	PS099	Spanish Pt A1	99	0	90	C.S.Z.	10	0	95	0	-	5	0.1
QL052	PS099	Spanish Pt A2	100	0	70	C.S.Z.	7	0	95	0	-	5	0
QL061	PS015	Glenasmole B1	100	189	50	-	11	70	90	0	-	0	10
QL067	PS012	County River A Casc	98	187	70	-	8	90	100	0	-	0	0
QL081	PS101	Kilgarrow A	95	108	80	-	6	75	97	0	-	3	0
QL083	PS076	Balscadden Beach	99	5	80	C.S.Z.	3	0	30	0	-	30	0
QL128	PS058	Gleniff Waterfall	99	283	60	-	11	0	100	0	-	0	5
QL154	PS022	N. of Skerries B	100	5	85	C.S.Z.	4	0	100	0	-	0	0
QL185	PS112	Glenregan A	100	145	65	-	11	95	100	0	-	0	0
QL213	PS118	Rathcor B	71	9	70	C.S.Z.	9	0	100	0	-	0	0
QL216	PS091	Ardmore Pt C	99	4	90	C.S.Z.	4	0	100	0	-	0	0
QL219	PS013	Silver River	56	153	80	-	12	65	100	0	-	0	0
		Mean		**89**	**70**		**9**	**33**	**89**	**0**		**5**	**13**

MC Membership Coefficient (% measure of how well sample fits group)

Slope degrees (°)

Alt. Altitude (m)

C.S.Z. Coastal Spray Zone

<1km Within 1km of coast

Spp. Number of species

Can. % tree canopy cover

Casc. % ground surface with cascade tufa

Pal. % ground surface with paludal tufa

P. St. Strength of paludal tufa (1 = weak, 3 = strong)

NonT. Non-tufa; % ground surface lacking tufa

Flow. % ground surface with flowing or trickling water

Group 2: *Palustriella commutata-Geranium robertianum* Springheads

26 Samples (n)

0.16 Silhouette width

Relevé	Site	Name	MC	Alt.	Slope	Coast	Spp.	Can.	Casc.	Pal.	P. St.	NonT.	Flow.
QL005	PS015	Glenasmole A2	77	184	25	-	16	60	95	0	-	0	15
QL029	PS002	Knocksink Wd A1 Bars	91	123	10	-	16	70	5	80	2	5	10
QL030	PS002	Knocksink Wd A2	89	96	15	-	14	85	75	5	2	0	40
QL037	PS015	Glenasmole E	96	196	30	-	10	60	50	0	-	10	0
QL056	PS005	Knockree B	86	111	20	-	13	35	20	74	3	5	3
QL058	PS073	Coneyburrow Wd LB	97	148	15	-	14	65	25	15	2	5	0
QL059	PS074	Glinsk Grove A	99	178	40	-	11	80	95	0	-	0	0
QL060	PS074	Glinsk Grove B	99	190	40	-	9	10	30	20	2	10	0
QL069	PS068	R Barrow Mill Quarter	93	148	75	-	13	95	100	0	-	0	0
QL108	PS036	Ballincar	59	5	80	C.S.Z.	9	0	100	0	-	0	0
QL121	PS003	Ballyman Glen 4 Wd	99	87	5	-	8	75	0	80	3	20	0
QL125	PS057	Knocknarea Glen A	97	48	65	-	16	75	100	0	-	0	3
QL126	PS057	Knocknarea Glen B	91	52	70	-	13	90	100	0	-	0	0
QL141	PS003	Ballyman Glen 5 Casc	83	78	10	-	13	0	100	0	-	0	10
QL152	PS015	Glenasmole C1	87	195	35	-	17	80	100	0	-	0	8
QL181	PS008	Camcor A Bar	60	179	20	-	18	0	100	0	-	0	0
QL182	PS008	Camcor B2 LB	90	180	15	-	19	0	100	0	-	0	0
QL183	PS008	Camcor B1 SB	78	190	15	-	16	0	100	0	-	0	0
QL184	PS008	Camcor C	50	187	5	-	26	25	0	100	1	0	0
QL186	PS112	Glenregan B	95	167	70	-	19	85	100	0	-	0	25
QL191	PS039	Moneyduff 1	93	24	15	-	11	50	100	0	-	0	0
QL193	PS039	Moneyduff 2	97	13	10	-	15	70	0	90	3	0	10
QL194	PS038	Glencar Waterfall A	65	70	80	-	16	95	45	50	2	5	0
QL195	PS038	Glencar (Wood) B	86	120	75	-	11	50	90	0	-	10	0
QL212	PS116	Murlough Bay B	47	171	55	<1km	17	0	80	0	-	20	70
QL217	PS101	Kilgarrow B2	93	122	35	-	7	70	100	0	-	0	25
		Mean		**125**	**36**		**14**	**51**	**70**	**20**		**3**	**8**

MC Membership Coefficient (% measure of how well sample fits group)

Slope degrees (°)

Alt. Altitude (m)

C.S.Z. Coastal Spray Zone

<1km Within 1km of coast

Spp. Number of species

Can. % tree canopy cover

Casc. % ground surface with cascade tufa

Pal. % ground surface with paludal tufa

P. St. Strength of paludal tufa (1 = weak, 3 = strong)

NonT. Non-tufa; % ground surface lacking tufa

Flow. % ground surface with flowing or trickling water

Group 3: *Brachythecium rivulare-Platyhypnidium riparioides* Tufaceous Streams & Flushes

29 Samples (n)

-0.01 Silhouette width

Relevé	Site	Name	MC	Alt.	Slope	Coast	Spp.	Can.	Casc.	Pal.	P. St.	NonT.	Flow.
QL004	PS015	Glenasmole A1	93	175	10	-	16	30	0	50	1	50	25
QL006	PS015	Glenasmole A3	56	166	10	-	16	80	20	10	1	55	30
QL021	PS032	Broadboyne Br. 1 Wd	83	31	30	-	8	15	100	0	-	0	13
QL022	PS032	Broadboyne Br. 2 Str	83	28	15	-	14	90	100	0	-	0	50
QL023	PS032	Broadboyne Br. 3	58	20	47	-	10	0	100	0	-	0	0
QL026	PS082	Camcor S. side 2	85	175	12	-	25	70	0	40	2	40	50
QL040	PS002	Knocksink 'Bog Meadow'	32	70	25	-	21	25	100	0	-	0	0.5
QL053	PS005	Knockree A3	74	112	25	-	18	80	0	10	2	35	59
QL054	PS005	Knockree A2	61	104	20	-	12	70	0	50	2	25	1
QL055	PS005	Knockree A1	76	116	10	-	10	75	10	20	2	10	20
QL057	PS073	Coneyburrow Wd SB	84	158	35	-	13	80	75	0	-	5	0
QL064	PS015	Glenasmole B5	74	173	25	-	20	75	90	0	-	0	40
QL070	PS054	Keelhilla NR B W'fall	61	166	55	-	5	60	40	0	-	50	40
QL098	PS015	Glenasmole B6	72	180	25	-	16	85	75	0	-	0	85
QL155	PS022	N. of Skerries C SB	35	5	30	C.S.Z.	3	0	100	0	-	0	15
QL156	PS018	Fonthill B1	77	25	25	-	6	95	10	0	-	90	40
QL157	PS018	Fonthill B2	79	25	5	-	12	50	0	0	-	75	90
QL158	PS018	Fonthill A	55	25	40	-	4	80	100	0	-	0	0
QL159	PS109	Woodlands	72	64	60	-	2	55	100	0	-	0	50
QL167	PS110	Kiltown	65	168	5	-	18	65	0	50	1	50	5
QL172	PS045	Hartwell Upr A1 LB	85	112	25	-	16	0	100	0	-	0	50
QL173	PS045	Hartwell Upr A2 SB	96	120	25	-	15	0	100	0	-	0	30
QL174	PS045	Hartwell Upr A3 Ert	92	111	25	-	11	0	100	0	-	0	80
QL175	PS045	Hartwell Upr A4	94	121	45	-	15	25	100	0	-	0	50
QL187	PS015	Glenasmole C7 LB	96	158	30	-	26	70	0	18	2	2	80
QL188	PS015	Glenasmole C6 MB	96	165	20	-	19	95	70	0	-	0	40
QL189	PS015	Glenasmole C5 TB	96	180	25	-	21	0	40	0	-	0	60
QL190	PS015	Glenasmole C4	70	195	20	-	17	65	100	0	-	0	45
QL209	PS116	Murlough Bay A2	47	170	60	<1km	10	25	70	0	-	10	25
		Mean		**114**	**27**		**14**	**50**	**59**	**9**		**17**	**37**

MC Membership Coefficient (% measure of how well sample fits group)

Slope degrees (°)

Alt. Altitude (m)

C.S.Z. Coastal Spray Zone

<1km Within 1km of coast

Spp. Number of species

Can. % tree canopy cover

Casc. % ground surface with cascade tufa

Pal. % ground surface with paludal tufa

P. St. Strength of paludal tufa (1 = weak, 3 = strong)

NonT. Non-tufa; % ground surface lacking tufa

Flow. % ground surface with flowing or trickling water

Group 4: *Palustriella commutata-Agrostis stolonifera* Springheads

28 Samples (n)

0.04 Silhouette width

Relevé	Site	Name	MC	Alt.	Slope	Coast	Spp.	Can.	Casc.	Pal.	P. St.	NonT.	Flow.
QL011	PS015	Glenasmole B4	85	190	25	-	24	0	33	0	-	34	20
QL014	PS041	Inis Meáin	89	12	5	<1km	11	0	0	1	2	99	10
QL015	PS049	Feenagh	56	148	5	-	22	0	0	70	2	10	25
QL018	PS046	Hartwell Lwr A1	71	112	0	-	22	0	0	90	3	10	10
QL025	PS082	Camcor S. side 1	61	182	16	-	28	80	0	84.5	2	15	0
QL036	PS091	Ardmore Pt B2	17	9	45	C.S.Z.	12	0	20	10	1	65	5
QL048	PS015	Glenasmole F	57	202	45	-	23	0	80	10	1	10	0
QL062	PS015	Glenasmole B2	90	184	20	-	20	0	50	0	-	40	20
QL063	PS015	Glenasmole B3	97	176	30	-	16	5	90	0	-	0	50
QL068	PS012	County R. B Seep	63	189	15	-	20	80	0	50	3	50	0
QL079	PS055	Seven Springs A1	75	125	10	-	26	0	0	70	2	30	10
QL080	PS003	Ballyman Glen 1	66	90	10	-	15	0	80	20	3	0	0
QL082	PS101	Kilgarrow B1	76	140	15	-	37	55	0	25	1	50	20
QL099	PS045	Hartwell Upr B	72	128	25	-	22	0	0	100	3	0	40
QL102	PS046	Hartwell Lwr A2	68	111	5	-	21	0	0	90	3	10	10
QL107	PS059	Corhawnagh Casc	39	34	10	-	19	0	100	0	-	0	10
QL130	PS106	Cormac Reagh 1 SH	70	185	25	-	12	0	0	100	1	0	0
QL148	PS070	Glenbarrow	44	218	20	-	28	0	80	5	1	15	0
QL150	PS015	Glenasmole C2	67	195	15	-	21	0	100	0	-	0	25
QL151	PS015	Glenasmole C3	83	195	20	-	30	0	75	20	2	0	20
QL153	PS022	N. of Skerries A LB	96	5	45	C.S.Z.	16	0	90	0	-	0	1
QL160	PS017	Carlingford Marina	86	13	60	<1km	23	0	0	1	1	99	30
QL192	PS039	Moneyduff Wood 3	67	16	5	-	16	20	0	95	2	0	10
QL202	PS114	Arroo Mt B1	55	284	55	-	11	0	20	30	2	20	25
QL206	PS004	Pollardstown C3 NM	57	86	0	-	19	0	0	100	3	0	0
QL210	PS117	Marconi's Cottage	69	23	80	<1km	12	0	90	0	-	10	0
QL214	PS118	Rathcor A1 Casc	85	6	60	C.S.Z.	11	0	99	0	-	1	0
QL215	PS118	Rathcor A2 Seep	43	9	55	C.S.Z.	15	0	0	100	2	0	0
		Mean		**117**	**26**		**20**	**9**	**36**	**38**		**20**	**12**

MC Membership Coefficient (% measure of how well sample fits group)

Slope degrees (°)

Alt. Altitude (m)

C.S.Z. Coastal Spray Zone

<1km Within 1km of coast

Spp. Number of species

Can. % tree canopy cover

Casc. % ground surface with cascade tufa

Pal. % ground surface with paludal tufa

P. St. Strength of paludal tufa (1 = weak, 3 = strong)

NonT. Non-tufa; % ground surface lacking tufa

Flow. % ground surface with flowing or trickling water

Group 5: *Schoenus* Springs

22 Samples (n)

0.17 Silhouette width

Relevé	Site	Name	MC	Alt.	Slope	Coast	Spp.	Can.	Casc.	Pal.	P. St.	NonT.	Flow.
QL016	PS065	Ballycurrin Fen 1	100	14	0	-	19	0	0	1	1	99	0
QL017	PS065	Ballycurrin Fen 2	100	12	0	-	22	0	0	1	1	99	0
QL035	PS091	Ardmore Pt B1	48	13	65	C.S.Z.	14	0	0	30	1	70	1
QL071	PS054	Keelhilla NR A1	39	139	0	-	28	0	0	65	2	35	5
QL072	PS054	Keelhilla NR A2	75	137	0	-	26	0	0	30	2	70	5
QL085	PS016	Ballynafagh B	75	89	0	-	14	0	0	40	2	60	0
QL089	PS104	Rinnamona L. Fen 2	93	31	0	-	22	0	0	5	1	95	0
QL091	PS065	Ballycurrin Fen 3	100	16	0	-	26	0	0	40	2	60	0
QL092	PS065	Ballycurrin Fen 4	100	13	0	-	18	0	0	80	3	20	0
QL094	PS028	Dooaghtry Flush 2	37	10	0	<1km	23	0	0	80	2	20	0
QL095	PS030	Eskeragh 1	100	61	0	-	20	0	0	95	3	0	0
QL096	PS030	Eskeragh 2	100	63	0	-	20	0	0	75	3	25	0
QL097	PS030	Eskeragh 3	100	63	0	-	9	0	0	80	3	20	0
QL104	PS059	Corhawnagh Fen 1	80	35	5	-	23	0	0	95	3	5	0
QL105	PS059	Corhawnagh Fen 2	100	31	5	-	17	0	0	100	3	0	0
QL106	PS059	Corhawnagh Fen 3	100	31	0	-	16	0	0	55	3	45	0
QL131	PS106	Cormac Reagh 2 Seep	42	183	20	-	52	0	0	60	2	40	0
QL132	PS106	Cormac Reagh 3 Fl	64	175	15	-	22	0	0	0	-	5	35
QL149	PS086	Clonaslee, Coolagh	98	87	0	-	12	0	0	50	1	50	0
QL177	PS078	Lisduff Fen 2	86	69	0	-	20	0	0	100	2	0	0
QL178	PS078	Lisduff Fen 3	94	75	0	-	28	0	0	100	1	0	0
QL207	PS004	Pollardstown B PE	82	87	0	-	26	0	0	100	3	0	0
		Mean		**65**	**5**		**22**	**0**	**0**	**58**		**37**	**2**

MC Membership Coefficient (% measure of how well sample fits group)

Slope degrees (°)

Alt. Altitude (m)

C.S.Z. Coastal Spray Zone

<1km Within 1km of coast

Spp. Number of species

Can. % tree canopy cover

Casc. % ground surface with cascade tufa

Pal. % ground surface with paludal tufa

P. St. Strength of paludal tufa (1 = weak, 3 = strong)

NonT. Non-tufa; % ground surface lacking tufa

Flow. % ground surface with flowing or trickling water

Group 6: *Carex lepidocarpa* Small Sedge Springs

30 Samples (n)

0.09 Silhouette width

Relevé	Site	Name	MC	Alt.	Slope	Coast	Spp.	Can.	Casc.	Pal.	P. St.	NonT.	Flow.
QL019	PS044	Kingsbog	90	82	0	-	33	0	0	50	2	50	0
QL020	PS077	Knocknatulla	73	66	0	-	32	0	0	1	1	99	0
QL024	PS081	Shannon Harbour	46	39	0	-	17	0	0	80	2	20	0
QL027	PS084	Black Head A	57	48	21	<1km	45	0	0	5	2	90	20
QL031	PS001	Louisa Bridge A	69	60	0	-	31	0	0	100	2	0	0
QL032	PS004	Pollardstown C2	82	86	3	-	30	0	0	30	3	70	0
QL033	PS004	Pollardstown C1 Tr	78	84	1	-	25	0	0	20	2	80	0
QL077	PS055	Seven Springs A2	60	121	10	-	31	0	0	80	3	15	10
QL078	PS055	Seven Springs B	77	123	0	-	21	0	0	50	1	50	0
QL084	PS048	Howth (Upr Cliff Rd)	73	73	0	<1km	20	0	0	20	1	80	0
QL087	PS103	Rinnamona L. Spring	71	32	5	-	21	10	0	50	2	39	80
QL100	PS045	Hartwell Upr C1	83	129	5	-	25	0	0	20	1	80	0
QL101	PS045	Hartwell Upr C2	86	127	5	-	21	0	0	30	1	68	0
QL103	PS046	Hartwell Lwr A3	97	111	5	-	22	0	0	80	2	20	0
QL119	PS003	Ballyman Glen 2 Tr	91	80	5	-	21	0	0	90	2	10	0
QL120	PS003	Ballyman Glen 3 Pl	78	83	5	-	22	0	0	100	2	0	10
QL122	PS001	Louisa Br. B1	85	45	3	-	28	0	0	100	2	0	3
QL123	PS001	Louisa Br. B2	80	46	5	-	30	0	0	70	2	0	15
QL124	PS105	Ballybannon ASSI	93	49	5	-	30	0	0	0	-	100	0
QL138	PS025	Old Head	35	22	10	<1km	24	0	0	1	1	99	20
QL161	PS061	Faughalstown 1	95	63	3	-	32	0	0	50	2	50	0
QL162	PS061	Faughalstown 2	53	60	10	-	25	0	0	90	3	10	10
QL163	PS061	Faughalstown 3	95	62	5	-	29	0	0	95	2	5	0
QL164	PS061	Faughalstown 4	68	64	0	-	26	0	0	75	2	25	0
QL165	PS021	Kilrock Quarry 1	43	40	40	<1km	27	0	0	0	-	99	2
QL176	PS078	Lisduff Fen 1	67	73	0	-	23	0	0	75	2	25	0
QL179	PS001	Louisa Br. C	84	48	0	-	30	0	0	90	1	0	0
QL180	PS001	Louisa Br. B3	48	45	0	-	30	0	0	38	2	2	0
QL204	PS004	Pollardstown A1	96	89	0	-	36	0	0	20	1	80	0
QL205	PS004	Pollardstown A2 NM	83	88	0	-	17	0	0	10	1	90	0
		Mean		**71**	**5**		**27**	**0**	**0**	**51**		**45**	**6**

MC Membership Coefficient (% measure of how well sample fits group)

Slope degrees (°)

Alt. Altitude (m)

C.S.Z. Coastal Spray Zone

<1km Within 1km of coast

Spp. Number of species

Can. % tree canopy cover

Casc. % ground surface with cascade tufa

Pal. % ground surface with paludal tufa

P. St. Strength of paludal tufa (1 = weak, 3 = strong)

NonT. Non-tufa; % ground surface lacking tufa

Flow. % ground surface with flowing or trickling water

Group 7: *Palustriella falcata-Carex panicea* Springs

20 Samples (n)

0.08 Silhouette width

Relevé	Site	Name	MC	Alt.	Slope	Coast	Spp.	Can.	Casc.	Pal.	P. St.	NonT.	Flow.
QL065	PS093	Newtown 2	62	106	5	-	19	0	0	3	1	86	30
QL066	PS093	Newtown 3	87	103	10	-	25	0	0	25	1	45	50
QL073	PS093	Newtown 1	78	115	20	-	37	0	0	30	1	45	17
QL074	PS092	Glennamanagh A1	49	122	5	-	13	0	0	40	2	25	25
QL075	PS092	Glennamanagh A2	78	122	5	-	23	0	0	25	1	50	24
QL076	PS100	Acres Village	97	143	10	-	16	0	0	25	2	15	70
QL086	PS016	Ballynafagh A	59	85	0	-	17	0	0	35	2	65	0
QL088	PS104	Rinnamona L. Fen 1	94	34	5	-	19	0	0	25	1	75	0
QL093	PS028	Dooaghtry Flush 1	92	10	5	<1km	29	0	0	40	2	60	0
QL137	PS063	Knocknagur	90	115	5	-	34	0	0	0	-	100	0
QL139	PS099	Spanish Pt B	25	8	50	C.S.Z.	6	0	100	0	-	0	10
QL140	PS092	Glennamanagh B	36	137	20	-	19	0	0	25	1	25	15
QL168	PS096	Thomastown Quarry A1	95	49	0	-	15	0	0	75	2	0	0
QL169	PS096	Thomastown Quarry A2	93	40	0	-	24	0	0	65	2	0	0
QL170	PS096	Thomastown Quarry B	80	41	0	-	21	0	0	80	2	20	0
QL198	PS040	Eagle's Rock Lwr A1	97	181	25	-	27	0	30	20	3	10	20
QL199	PS040	Eagle's Rock Lwr A2	98	180	10	-	23	0	0	70	1	30	0
QL200	PS040	Eagle's Rock Lwr B	97	180	15	-	17	0	0	80	3	0	20
QL201	PS114	Arroo Mt A	96	185	10	-	26	0	100	0	-	0	10
QL203	PS114	Arroo Mt B2	63	275	35	-	32	0	0	40	2	25	25
		Mean		**112**	**12**		**22**	**0**	**12**	**35**		**34**	**16**

MC Membership Coefficient (% measure of how well sample fits group)

Slope degrees (°)

Alt. Altitude (m)

C.S.Z. Coastal Spray Zone

<1km Within 1km of coast

Spp. Number of species

Can. % tree canopy cover

Casc. % ground surface with cascade tufa

Pal. % ground surface with paludal tufa

P. St. Strength of paludal tufa (1 = weak, 3 = strong)

NonT. Non-tufa; % ground surface lacking tufa

Flow. % ground surface with flowing or trickling water

Group 8: *Saxifraga aizoides-Seligeria oelandica* Springs

13 Samples (n)

0.17 Silhouette width

Relevé	Site	Name	MC	Alt.	Slope	Coast	Spp.	Can.	Casc.	Pal.	P. St.	NonT.	Flow.
QL090	PS084	Black Head C W'fall	89	62	50	<1km	21	0	10	0	-	50	50
QL129	PS058	Gleniff Annacoona Upr	98	368	50	-	49	0	0	20	2	40	10
QL133	PS058	Gleniff Annacoona Lwr	97	281	35	-	42	0	0	20	2	40	25
QL134	PS058	Gleniff Annacoona Mid	98	307	60	-	43	0	0	20	1	45	0
QL135	PS107	Benbulbin Corrie	99	324	60	-	48	0	10	25	2	10	5
QL136	PS108	Benwiskin	98	327	70	-	39	0	20	35	2	25	5
QL166	PS021	Kilrock Quarry 2	48	32	5	<1km	31	0	0	0	-	95	0
QL171	PS111	Glencreawan Lough	83	225	25	-	26	0	0	25	1	50	0
QL196	PS113	Eagle's Rock (Cliff)	98	308	75	-	31	15	0	30	1	10	0
QL197	PS115	Larganavaddoge (Cliff)	98	369	70	-	36	0	0	45	1	30	0
QL208	PS116	Murlough Bay A1	51	178	55	<1km	21	0	80	15	2	5	0
QL211	PS116	Murlough Bay C	82	179	50	<1km	26	0	0	1	1	99	0
QL218	PS119	Magho Cliffs	91	201	80	-	27	0	0	0	-	20	10
		Mean		**243**	**53**		**34**	**1**	**9**	**18**		**40**	**8**

MC Membership Coefficient (% measure of how well sample fits group)

Slope degrees (°)

Alt. Altitude (m)

C.S.Z. Coastal Spray Zone

<1km Within 1km of coast

Spp. Number of species

Can. % tree canopy cover

Casc. % ground surface with cascade tufa

Pal. % ground surface with paludal tufa

P. St. Strength of paludal tufa (1 = weak, 3 = strong)

NonT. Non-tufa; % ground surface lacking tufa

Flow. % ground surface with flowing or trickling water

Appendix III: Synoptic Table

Key to Synoptic Table:

FC Fuzzy Cluster Group in which species has highest ISA score
F Frequency in Group — Significant by ISA and MPA — Significant by MPA
Min Minimum % cover value in Group
Max Maximum % cover value in Group
ISA Indicator Species Analysis: *** p<0.001; ** p<0.01; * p<0.05
186R % frequency in all relevés (n=186)
MPA Multi-level Pattern Analysis: *** p<0.001; ** p<0.01; * p<0.05

FC	Species	1 F	1 Min	1 Max	1 ISA	2 F	2 Min	2 Max	2 ISA	3 F	3 Min	3 Max	3 ISA	4 F	4 Min	4 Max	4 ISA	5 F	5 Min	5 Max	5 ISA	6 F	6 Min	6 Max	6 ISA	7 F	7 Min	7 Max	7 ISA	8 F	8 Min	8 Max	8 ISA	186R	MPA
	ALL GROUPS / WIDESPREAD																																		
2	Palustriella commutata	IV	2	60		V	25	90	***	IV	1	35		V	10	95		III	0.5	55		IV	1	80		III	1	20		IV	0.1	15		75%	
4	Agrostis stolonifera	IV	0.1	3		III	1	15		V	0.1	25		V	0.5	10	**	II	0.1	5		III	0.1	20		IV	0.5	10		V	0.5	10		66%	***
8	Festuca rubra	III	0.1	3		I	0.5	3		I	0.1	5		V	0.1	55		III	0.5	40		V	1	40		III	0.5	10		V	2	15	***	54%	***
8	Carex flacca	I	0.5	1		I	1	10		I	0.1	5		IV	0.5	35		II	0.5	10		IV	1	40		V	0.5	10		V	0.5	20	**	51%	***
1	Pellia endiviifolia	IV	1	70	**	IV	0.1	10		III	0.1	50		II	1	30		I	0.1	1		II	0.1	2		I	0.5	30		V	0.1	10		40%	***
6	Bryum pseudotriquetrum	I	0.5	1		I	4	4		I	0.1	45		III	0.1	40		II	0.1	0.5		IV	0.1	20	*	IV	0.1	2		IV	0.1	5		38%	***
3	Cratoneuron filicinum	I	0.1	5		II	3	10		IV	0.1	85	*	III	0.1	50						II	0.1	40		I	0.1	30		II	1	60		33%	**
	GROUPS 1-4																																		
1	Eucladium verticillatum	V	2	70	***	III	0.1	10		I	0.5	2		I	0.1	10		I	1	2		I	0.5	0.5						I	0.1	0.2		23%	***
1	Didymodon tophaceus	III	0.1	20	***	II	0.1	3		I	0.1	20		II	0.1	10		I	5	5		I	5	5						II	0.1	1		16%	**
1	Conocephalum conicum agg.	I	3	5		I	1	45		I	0.1	5																		I	0.1	0.1		7%	*
1	Cochlearia officinalis	I	0.5	0.5		I	0.5	0.5		I	1	1																						2%	
2	Geranium robertianum	II	0.5	3		IV	0.1	40	***	III	0.1	30		II	0.1	1																		25%	***
2	Equisetum telmateia					III	0.1	15	*	II	0.1	60		II	0.1	25						I	5	10		I	0.1	1						18%	***
2	Carex remota					II	1	15	**	II	0.5	40		I	5	5																		9%	***
2	Chrysosplenium oppositifolium					II	0.5	20	*	II	0.5	3		I	0.5	0.5																		8%	**
3	Brachythecium rivulare	I	0.1	3		II	0.1	10		V	0.1	40	***	II	0.5	25		I	0.1	0.1		I	0.5	10										26%	***
3	Platyhypnidium riparioides					I	15	15		II	0.1	80	***																					5%	***
3	Glyceria notata									I	0.1	25	*	I	0.5	5																		4%	*
-	Chroothece sp.	I	1	1										I	5	5																		1%	

FC	Species	F	Min	Max	ISA	F	Min	Max	ISA	F	Min	Max	ISA	F	Min	Max	ISA	F	Min	Max	ISA	F	Min	Max	ISA	186R	MPA
		1				2				3				4				5				6				7				8					
	GROUPS 5-8																																
5	Schoenus nigricans	I	3	3										I	1	45		V	15	65	***	II	1	20		I	0.5	5						21%	***
5	Campylium stellatum													I	0.5	15		V	1	65	***	III	0.5	30		II	0.1	80						25%	***
5	Selaginella selaginoides	I	0.1	0.1														III	0.1	1	**	I	0.1	5		II	0.5	2		II	0.1	0.1		13%	***
5	Scorpidium cossonii													I	1	1		III	0.1	50	***	II	0.1	60		I	5	5						12%	***
5	Scorpidium scorpioides																	III	2	65	***					I	3	3						5%	***
5	Pinguicula lusitanica																	I	0.1	1	*	I	0.5	0.5		I	0.1	0.1						4%	*
5	Chara vulgaris													I	0.5	2		I	1	30		II	0.5	5		I	0.5	2						10%	**
5	Potamogeton coloratus																	I	1	3		I	0.5	0.5		I	2	4						4%	*
5	Carex hostiana													I	0.5	0.5		I	0.5	3		I	5	5										3%	
5	Cirsium dissectum																	I	0.1	5	*	I	0.1	0.1										2%	*
5	Eriophorum latifolium													I	1	1		I	1	1		I	1	1										2%	
-	Cladium mariscus																	I	3	10														1%	
-	Dactylorhiza majalis ssp. traunsteineroides																	I	0.1	0.5														1%	
-	Leiocolea bantriensis																	I	1	1										I	0.5	0.5		1%	
-	Utricularia australis/vulgaris																	I	2	20														1%	
6	Carex lepidocarpa	I	1	1										II	0.5	30		III	0.1	20		IV	2	45	***	V	0.5	15		II	1	10		38%	***
6	Anagallis tenella	I	0.1	0.1										I	0.1	0.5		III	0.1	2		III	0.1	20	***	II	0.5	20						20%	***
6	Eriophorum angustifolium													I	0.1	0.5		II	0.1	3		III	0.1	10	**	I	0.1	15		I	1	25		15%	***
6	Triglochin palustris													I	1	5		I	0.1	0.5		II	0.1	20	***	I	0.5	0.5						12%	**
6	Eleocharis quinqueflora																	II	0.1	20		II	0.1	15		I	5	10						11%	***
6	Plagiomnium elatum													II	0.1	5						II	0.1	3	*	I	0.1	1						9%	***
6	Juncus subnodulosus													I	2	10		II	0.5	15		II	3	75	*	I	15	15						9%	***
6	Pedicularis palustris																	I	0.1	0.1		II	0.5	10	***									4%	***
6	Carex dioica																	I	0.5	0.5		I	0.1	5		I	0.5	3		I	0.1	1		6%	**
6	Dactylorhiza incarnata																	I	0.1	0.1		I	0.5	0.5										2%	
7	Palustriella falcata	I	5	25										I	2	15		III	1	10		II	0.5	10		V	1	75	***	III	0.5	40		26%	***
7	Carex panicea	I	0.5	0.5										II	0.5	5		III	0.1	10		V	0.5	15		V	0.5	40	***	II	1	10		36%	***
7	Philonotis calcarea	I	1	1										I	0.5	20		II	0.5	15		II	0.1	10		III	0.1	40	**	II	0.1	1		19%	***
7	Pinguicula grandiflora																									II	0.1	3	***					3%	***
8	Saxifraga aizoides													I	5	5										I	2	2		V	0.5	15	***	7%	***
8	Jungermannia atrovirens					I	0.5	0.5						I	0.1	0.1		I	0.1	0.5						I	0.1	3		IV	0.1	5	***	10%	***
8	Aneura pinguis	I	0.1	1		I	10	10						I	0.1	3		III	0.1	5		III	0.1	2		III	0.1	2		IV	0.1	5	***	29%	***
8	Sesleria caerulea	I	5	5		I	3	3						I	3	3		I	0.5	2		I	3	3		I	0.5	3		IV	1	15	***	10%	***
8	Breutelia chrysocoma	I	3	3										I	10	10		II	0.1	40		I	1	10		II	0.1	10		IV	0.1	4	*	13%	***
8	Fissidens adianthoides					I	0.5	3		I	3	3		I	0.1	0.5		II	0.1	2		I	0.1	3		I	0.5	10		III	0.1	1	**	13%	*
8	Pinguicula vulgaris	I	1	1										I	0.1	0.5		III	0.5	2		II	0.1	15		II	1	2		III	0.5	2	*	19%	***

Appendix III: Synoptic Table

FC	Species	1 F	1 Min	1 Max	1 ISA	2 F	2 Min	2 Max	2 ISA	3 F	3 Min	3 Max	3 ISA	4 F	4 Min	4 Max	4 ISA	5 F	5 Min	5 Max	5 ISA	6 F	6 Min	6 Max	6 ISA	7 F	7 Min	7 Max	7 ISA	8 F	8 Min	8 Max	8 ISA	186R	MPA
8	Orthothecium rufescens																	I	0.5	0.5										III	0.1	5	***	4%	***
8	Seligeria oelandica	I	1	1														I	0.5	2						I	0.1	0.1		III	0.5	5	***	5%	***
8	Bellis perennis					I	0.5	0.5						I	0.5	0.5						I	0.1	0.5		I	0.1	5		III	0.1	1	***	8%	***
8	Parnassia palustris																	I	0.1	0.1		II	0.1	5		II	0.1	1		III	0.1	1	**	12%	***
8	Seligeria patula	I	0.1	0.1																										III	0.1	5	***	4%	***
8	Dicranella varia					I	0.1	0.1						I	0.1	0.1														III	0.1	0.5	***	5%	***
8	Campanula rotundifolia													I	3	3														III	0.1	2	***	4%	***
8	Hymenostylium insigne					I	3	3																						III	0.1	5	***	4%	***
8	Hymenostylium recurvirostrum	I	1	1		I	1	1										I	0.1	0.1						I	0.1	0.1		II	0.1	3	***	4%	***
8	Gymnostomum aeruginosum													I	1	1										I	1	1		II	0.1	1	***	3%	**
8	Alchemilla glabra					I	0.5	0.5																						II	0.1	1	***	3%	***
8	Tussilago farfara	I	0.5	3										I	0.1	5										I	0.1	1		II	0.5	5	**	7%	**
8	Pohlia wahlenbergii	I	0.5	0.5		I	0.1	0.1		I	0.1	0.5																		II	0.1	0.2	**	5%	**
8	Preissia quadrata																	I	0.1	2						I	0.1	0.1		I	0.1	2		3%	*
8	Leiocolea collaris																	I	0.1	0.1										I	0.1	1	*	2%	*
-	Hieracium cf. anglicum																													I	0.5	1		1%	
-	Hygrohypnum luridum																													I	0.1	5		1%	
	DISPERSED ACROSS GROUPS																																		
4	Crepis paludosa					I	2	2		I	1	2		I	2	10						I	1	5		I	0.5	0.5		I	0.5	0.5		9%	
4	Lysimachia nemorum					I	0.1	0.1		I	0.5	0.5		I	1	2														I	0.5	0.5		3%	
1	Plantago maritima	II	0.5	10										I	2	5		I	0.5	10		I	5	5		I	0.5	3		I	2	5		10%	*
1	Carex distans	I	3	3										I	1	1		I	3	3														2%	
5	Samolus valerandi	I	0.5	0.5										I	1	1		I	0.5	3		I	0.1	0.1		I	0.1	0.5		I	0.5	0.5		5%	
6	Isolepis cernua													I	0.5	0.5		I	1	1		I	0.1	1										2%	
6	Galium uliginosum													I	0.1	1						I	0.1	1										3%	
7	Equisetum variegatum													I	0.5	3		I	3	3		I	2	2		I	20	20						3%	
	WIDESPREAD; LOW ECOLOGICAL SIGNIFICANCE																																		
3	Ranunculus repens					II	0.1	30		III	0.5	40	***	I	1	3		I	0.5	0.5		I	0.5	1		I	0.1	1		II	0.5	1		17%	***
3	Nasturtium officinale agg.					I	1	5		II	0.5	55	*	II	0.1	10		I	1	1		I	0.5	10		I	0.1	0.5						13%	
2	Fraxinus excelsior	I	0.1	0.1		III	0.1	5		II	0.1	5		II	0.1	0.5		I	0.1	0.5		II	0.1	1		I	0.1	0.5						25%	*
4	Eupatorium cannabinum	I	1	1		II	0.1	5		I	0.1	3		II	2	45		I	0.5	1		II	0.1	10		I	0.1	3		I	0.1	0.1		22%	*
4	Filipendula ulmaria					II	0.1	2		II	0.1	3		III	0.5	10	**	I	1	1		I	0.1	1						II	0.1	1		18%	**
6	Holcus lanatus					II	0.5	5		I	1	45		II	0.1	3						II	0.5	10		I	0.1	1		I	1	1		17%	*
6	Mentha aquatica	I	0.5	0.5		I	0.5	2		III	0.5	15		III	0.1	10		II	0.1	1		IV	0.1	5	**	II	0.5	1						32%	***
8	Thuidium tamariscinum					I	0.1	0.5		I	0.1	10		I	0.1	2		I	0.1	0.1		I	1	1		I	0.1	0.1		II	0.1	0.5	*	9%	
8	Taraxacum officinale agg.					I	0.1	0.1		I	0.1	1		II	0.1	2		I	0.1	0.1		I	0.1	1		II	0.1	2		IV	0.1	2	**	20%	***

FC	Species	1 F	1 Min	1 Max	1 ISA	2 F	2 Min	2 Max	2 ISA	3 F	3 Min	3 Max	3 ISA	4 F	4 Min	4 Max	4 ISA	5 F	5 Min	5 Max	5 ISA	6 F	6 Min	6 Max	6 ISA	7 F	7 Min	7 Max	7 ISA	8 F	8 Min	8 Max	8 ISA	186R	MPA
	WIDESPREAD IN OR RESTRICTED TO GROUPS 1-4																																		
3	Plagiomnium undulatum	I	1	1		II	0.1	0.5		II	0.1	30		II	0.1	1						I	0.5	1						I	0.1	0.1		13%	
3	Cardamine flexuosa					I	0.1	1		I	0.5	1		I	0.1	0.1						I	0.1	0.1										5%	*
3	Plagiomnium rostratum	I	1	1		I	0.1	0.1		I	0.1	0.5																						3%	
3	Ficaria verna	I	0.1	0.1		I	0.1	1		I	0.1	2		I	0.5	0.5																		6%	*
3	Brachypodium sylvaticum	I	0.1	2		II	0.1	10		II	0.5	15	*	I	0.5	1																		11%	**
2	Poa trivialis	I	0.5	0.5		II	0.1	1		II	0.1	3		I	0.5	20		I	1	1		I	3	3						I	5	5		13%	*
2	Hedera helix	II	0.5	1		II	0.1	5	**	II	0.1	2										I	0.5	0.5										15%	***
2	Asplenium scolopendrium	I	0.5	0.5		II	0.5	10	**	I	0.5	3																						5%	**
2	Rubus fruticosus	I	0.5	0.5		III	0.5	10	***	II	0.5	3		I	0.1	2																		12%	***
2	Thamnobryum alopecurum	I	0.5	2		I	0.5	15		I	1	1																						4%	*
2	Glechoma hederacea					I	0.1	0.5		I	1	1		I	0.1	0.1																		3%	
2	Lonicera periclymenum					I	1	3		I	0.1	1																						3%	*
2	Oxalis acetosella					I	0.1	0.5						I	0.1	0.5																		2%	
4	Ajuga reptans					I	1	2		I	5	5		I	0.1	3																		3%	
6	Cardamine pratensis	I	0.1	0.1		II	0.1	2		II	0.1	5		II	0.1	3						III	0.1	10	*					I	0.1	0.5		23%	***
-	Geum rivale									I	0.5	0.5		I	15	15																		1%	
	WIDESPREAD IN GROUPS 5-8																																		
5	Calluna vulgaris																	I	0.1	3	*	I	1	1		I	0.5	0.5		I	0.5	0.5		4%	*
5	Carex pulicaris																	II	1	5	*	I	0.1	0.1		I	0.1	1		I	1	1		6%	**
5	Ctenidium molluscum					I	5	5						I	1	1		IV	0.1	20	***	II	0.5	20		II	0.1	10		IV	0.5	10		22%	***
5	Dactylorhiza fuchsii																	I	0.1	0.5		I	0.1	1										3%	*
5	Drosera rotundifolia																	I	0.1	2	*	I	0.5	0.5		I	0.5	0.5						3%	
5	Frullania tamarisci																	I	1	1										I	0.1	0.1		2%	
5	Juncus bufonius agg.																	I	1	1						I	0.1	1						2%	*
5	Lotus corniculatus																	I	0.1	0.1		I	0.1	0.1										2%	
5	Molinia caerulea	I	1	1										I	5	5		IV	1	40	***	III	0.1	75		II	0.5	2		I	1	5		25%	***
5	Phragmites australis													I	0.1	3		II	0.1	3	**	I	0.5	3										9%	**
5	Polygala vulgaris													I	0.5	0.5		I	0.5	1		I	0.1	0.1		I	0.1	0.5		I	0.5	0.5		4%	
5	Potentilla erecta					I	0.5	0.5						I	0.5	0.5		III	0.1	5	***	III	0.1	10		II	0.1	0.5						18%	***
5	Pseudoscleropodium purum													I	0.1	0.1		I	0.1	1		I	3	5						I	0.1	0.1		4%	
6	Calliergonella cuspidata					I	0.1	5		I	0.5	0.5		IV	0.1	30		II	0.1	10		IV	0.1	70	***	III	0.1	5		IV	0.1	10		39%	**
6	Caltha palustris																					I	0.5	3	*									2%	*
6	Carex disticha													I	1	1						I	0.5	10	*									3%	*
6	Carex echinata																					I	0.5	1		I	0.1	0.1		I	0.1	0.1		2%	
6	Carex nigra																	I	0.1	1		II	0.1	20	**	I	0.1	3						7%	**

Appendix III: Synoptic Table

FC	Species	1 F	1 Min	1 Max	1 ISA	2 F	2 Min	2 Max	2 ISA	3 F	3 Min	3 Max	3 ISA	4 F	4 Min	4 Max	4 ISA	5 F	5 Min	5 Max	5 ISA	6 F	6 Min	6 Max	6 ISA	7 F	7 Min	7 Max	7 ISA	8 F	8 Min	8 Max	8 ISA	186R	MPA
6	Carex rostrata																	I	0.5	1		I	3	40	*	I	0.5	20						5%	*
6	Equisetum arvense					I	0.1	0.1		I	0.5	0.5		I	0.1	2		I	0.1	0.1		I	0.5	10		II	0.1	0.5		I	0.5	1		11%	**
6	Equisetum fluviatile																					I	0.1	60	*	I	0.5	0.5						3%	*
6	Equisetum palustre									I	0.1	0.1		II	0.1	5		II	0.1	10		III	0.1	20	***	I	1	10		II	0.5	2		22%	***
6	Hydrocotyle vulgaris																	II	0.1	10		I	0.1	35		I	0.1	10						6%	**
6	Juncus articulatus					I	0.1	2		I	0.5	0.5		IV	0.1	20		II	2	5		IV	0.1	25	**	IV	0.5	3		IV	0.1	10		39%	***
6	Menyanthes trifoliata																	I	20	25		I	1	40	*									4%	**
6	Pulicaria dysenterica																					I	1	1		I	0.1	0.1						2%	
6	Succisa pratensis	I	0.5	0.5										I	0.5	2		III	0.5	20		V	0.5	25	***	III	0.1	10		III	0.5	3		31%	***
6	Valeriana officinalis																	I	1	1		I	0.5	3										2%	
7	Briza media	I	1	1										I	0.1	2		I	0.1	0.1		I	0.5	2		II	0.5	3	**					8%	**
7	Ditrichum gracile													I	1	1		I	0.1	0.1		I	1	1		I	1	1		I	0.1	0.1		3%	
7	Hypericum tetrapterum					I	1	1		I	0.1	0.5		I	0.1	0.1		I	0.1	0.1		I	0.1	0.5		II	0.1	0.5		I	0.1	0.1		9%	
7	Leontodon saxatilis																	I	1	1						I	1	3						2%	
7	Salix repens																	I	1	1		I	1	1		I	1	1						2%	
8	Campylium protensum																	I	1	1										I	0.1	0.2	*	2%	*
8	Cirsium palustre					I	0.5	1		I	1	1		II	0.1	10		I	0.1	0.5		III	0.5	5		II	0.1	0.5		IV	0.1	2	**	23%	***
8	Dactylis glomerata									I	3	3		I	0.5	0.5														I	2	2		2%	
8	Didymodon fallax													I	0.1	0.1		I	0.1	0.1										I	0.1	0.1	*	2%	*
8	Epilobium brunnescens					I	0.1	0.1		I	0.5	0.5																		II	0.1	0.5	**	3%	***
8	Epilobium palustre					I	0.1	0.1										I	0.1	0.1		I	0.1	0.1						I	0.5	0.5		2%	
8	Hylocomium splendens																	I	0.1	0.1		I	10	10		I	0.1	0.1		I	0.1	0.5		3%	
8	Juncus bulbosus																					I	0.5	0.5		I	1	1		I	10	10		2%	
8	Linum catharticum																	I	0.1	0.5		I	0.1	0.1		I	0.1	0.1		IV	0.1	0.5	***	10%	***
8	Primula vulgaris					I	0.5	0.5		I	1	1		I	3	3														II	0.5	1	**	3%	*
8	Prunella vulgaris													I	0.5	1		I	0.1	0.1		II	0.1	5		I	0.1	0.5		III	0.1	2	***	14%	***
8	Rhinanthus minor																	I	0.1	0.1		I	0.1	0.1		I	0.1	0.1		I	0.1	0.1		2%	
8	Rhytidiadelphus squarrosus									I	0.1	0.1						I	0.1	0.1		I	5	5		I	0.1	0.1		II	0.1	0.5	**	5%	**
8	Riccardia chamedryfolia					I	0.1	0.1		I	5	5		I	0.5	0.5		II	0.1	0.1		I	0.1	0.1						II	0.1	2	*	8%	**
8	Scorzoneroides autumnalis													I	0.5	1						I	0.5	0.5		I	0.1	0.1		II	0.1	0.5	***	4%	**
8	Thymus polytrichus																	I	0.1	0.1		I	0.1	0.1						I	0.5	0.5		2%	
8	Tortella tortuosa																	I	0.5	0.5						I	0.1	0.1		I	0.1	0.1		2%	
	OTHER SPECIES (LOW ECOLOGICAL SIGNIFICANCE)																																		
3	Acer pseudoplatanus					I	2	2		I	0.1	0.5																		I	0.1	0.1		3%	
3	Apium nodiflorum									I	3	10	*	I	1	1		I	2	2		I	1	1		I	0.5	0.5						4%	
3	Lysimachia nummularia					I	0.5	0.5		I	0.5	15																						2%	

FC	Species	1 F	1 Min	1 Max	1 ISA	2 F	2 Min	2 Max	2 ISA	3 F	3 Min	3 Max	3 ISA	4 F	4 Min	4 Max	4 ISA	5 F	5 Min	5 Max	5 ISA	6 F	6 Min	6 Max	6 ISA	7 F	7 Min	7 Max	7 ISA	8 F	8 Min	8 Max	8 ISA	186R	MPA
3	Potentilla reptans					I	0.5	0.5		I	0.1	0.1		I	0.1	0.1										I	0.1	0.1						3%	
3	Ranunculus acris									I	0.5	1		I	1	1						I	0.1	0.1										3%	
2	Arrhenatherum elatius					I	0.5	1		I	1	1		I	0.5	1														I	0.1	0.1		5%	
2	Galium palustre					I	0.1	5		I	0.5	5										I	10	10										3%	
2	Juncus effusus					I	0.5	10		I	1	3						I	2	2										I	0.1	0.1		5%	
2	Pohlia melanodon					I	2	2						I	0.1	0.1														I	0.1	0.1		2%	
2	Veronica beccabunga					I	0.1	1		I	0.5	2		I	1	2						I	1	3										5%	
4	Juncus inflexus					I	1	20		I	1	1		II	1	10	*					II	0.5	10										13%	***
4	Lophocolea bidentata													I	0.5	30	*					I	0.5	1										3%	*
4	Potentilla anserina													I	2	2						I	1	1		I	0.5	0.5						2%	
4	Ranunculus flammula									I	0.5	0.5		II	0.1	10	*	I	2	2		I	0.5	3		I	2	2						8%	*
4	Schedonorus arundinaceus					I	1	1						I	2	15	*					I	3	3		I	1	1						4%	*
6	Centaurea nigra	I	1	1										I	0.5	3		I	1	1		I	0.5	3						I	1	1		4%	
6	Epilobium parviflorum					I	2	2		I	0.1	1		I	0.5	1						II	0.1	1	**									9%	*
6	Salix cinerea									I	10	10		I	1	1		I	0.5	3		II	0.1	5		I	0.1	0.1						7%	*
7	Anthoxanthum odoratum													I	0.1	1						I	0.5	5		I	0.5	2						4%	
7	Crataegus monogyna	I	0.1	0.1						I	0.1	0.1						I	0.1	0.1						I	0.1	0.1		I	0.1	0.1		4%	
7	Plantago lanceolata									I	2	2		I	0.1	0.1						I	0.5	1		I	0.5	1		I	0.5	1		5%	*
8	Angelica sylvestris									I	0.1	0.1		I	0.1	0.5		I	0.5	2		I	1	3						I	0.5	10		8%	
8	Deschampsia cespitosa					I	1	8		I	2	15		II	1	20						I	0.1	0.1						II	0.5	3	*	10%	**
8	Fissidens taxifolius	I	0.1	0.5		I	0.1	0.1		I	0.1	0.5		I	0.1	0.1		I	0.5	1						I	0.1	0.5		II	0.1	0.1		10%	
8	Leiocolea turbinata	I	0.5	0.5		I	0.1	0.1																						I	0.1	0.2	*	2%	
8	Rhytidiadelphus triquetrus					I	1	1										I	0.2	0.2										II	0.1	0.1	**	3%	*
8	Trichostomum crispulum					I	0.1	0.1		I	15	15						I	0.5	0.5						I	0.1	0.1		II	0.1	0.5	*	4%	*
-	Iris pseudacorus					I	5	5						I	0.5	0.5																		1%	
-	Plagiochila porelloides																	I	0.1	0.1										I	0.1	0.1		1%	
-	Rhizomnium punctatum									I	0.1	0.1		I	1	1																		1%	
-	Scrophularia auriculata									I	2	5																						1%	

FC Fuzzy Cluster Group in which species has highest ISA score

F Frequency in Group — Significant by ISA and MPA — Significant by MPA

Min Minimum % cover value in Group

Max Maximum % cover value in Group

ISA Indicator Species Analysis: *** p<0.001; ** p<0.01; * p<0.05

186R % frequency in all relevés (n=186)

MPA Multi-level Pattern Analysis: *** p<0.001; ** p<0.01; * p<0.05

Mean % cover in fuzzy cluster groups for selected variables

See Chapter 3 for figures

PLANT GROUP (Fig. 3.4)	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Forbs	1	8	15	12	8	19	6	9
Graminoids	2	9	14	33	54	60	23	28
Bryophytes	60	69	32	56	55	69	42	32
Woody plants ≤ 50cm	0	3	2	0	1	1	0	0
Pteridophytes	0	3	5	3	1	6	2	0
Total	65	92	68	105	119	155	74	70

TUFA TYPE (Fig. 3.6)	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Cascade	89	70	59	36	0	0	12	9
Paludal	0	20	9	38	58	51	35	18
Stream crust	6	0	7	2	1	0	13	33
Oncoids/ooids	1	5	8	3	4	1	4	0
Dam	0	2	1	0	0	0	0	0
Marl	0	0	0	0	0	2	3	0
Cemented pebbles	0	0	0	0	0	0	0	0
Non-tufa	5	3	17	20	37	45	34	40
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

PALUDAL STRENGTH (Fig. 3.6)	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Paludal 1 (weak)	0	4	4	5	9	8	10	9
Paludal 2 (intermediate)	0	7	5	17	19	36	20	9
Paludal 3 (strong)	0	9	0	16	31	7	5	0
Total	**0**	**20**	**9**	**38**	**58**	**51**	**35**	**18**

SURFACE COMPOSITION (Fig. 3.7)	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Living vegetation	65	76	54	68	54	76	48	50
Leaf litter/standing dead	3	9	8	13	28	13	7	6
Bare tufa	24	14	29	11	14	7	28	27
Bare stone	7	1	5	6	1	1	15	13
Bare soil	0	0	4	2	4	3	2	4
Other	1	0	1	0	0	0	1	0
Total	100	100	100	100	100	100	100	100

SURFACE WATER (Fig. 3.8)	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
Flowing/trickling	13	8	37	12	2	6	16	8
Pool	1	3	4	5	19	11	11	0
Dripping	18	7	1	3	0	0	0	12
Damp	61	81	52	75	75	82	60	74
Dry	8	0	6	5	4	1	13	5
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Appendix V: Chemical Analysis of Spring Water

Key to Table (overleaf)

WS	Water sample reference number
QL	Relevé (quadrat) reference number
QL Note	Exact: water sample collected inside quadrat;
	Equiv: water sample equivalent to quadrat (collected close-by)
	Comp: additional sample collected for comparison purposes
Fuzzy Cluster	Plant community to which corresponding relevé was assigned (Groups 1 - 8, Chapter 3)

Appendix V: Chemical Composition of Spring Water

WS	Location	pH	Alkalinity mg/l HCO_3^-	Ca^{2+} mg/l	Mg^{2+} mg/l	K^+ mg/l	Na^{2+} mg/l	Cl^- mg/l	NO_3^- mg/l	PO_4^{3-} µg/l	SO_4^{2-} mg/l	Ion Balance	QL	QL Note	Fuzzy Cluster	PS
2	Glenasmole STTC	8.03	268.2	80.06	6.72	1.04	8.36	10.53	2.95	17	10.01	1.00	150,151	Equiv.	4	PS015.1
4	Glenasmole STTB	8.03	279.6	82.04	8.20	0.93	8.55	11.41	2.88	19	11.75	0.99	189	Exact	3	PS015.1
6	Glenasmole SCMID	7.97	335.0	102.44	5.73	0.81	7.70	11.02	3.92	18	8.46	0.98	11	Equiv.	4	PS015.2
7	Hartwell Upr Stream	7.95	398.9	122.64	11.00	1.13	8.84	14.88	14.03	21	13.01	1.01	172-175	Comp.	3	PS045
8	Hartwell Upr Cascade	8.01	397.2	120.72	10.85	1.12	8.42	14.70	14.00	14	13.02	0.99	174	Exact	3	PS045
11	Hartwell Lwr Old Well	7.44	451.4	135.12	13.37	6.81	10.03	16.71	13.37	14	18.41	1.00	18	Equiv.	4	PS046
13	Louisa Bridge FP	7.80	289.6	105.02	29.60	9.44	210.92	410.22	0.11	16	47.93	0.99	31	Equiv.	6	PS001
14	Louisa Bridge EC	7.75	279.4	103.34	30.56	8.79	225.38	423.13	0.13	15	44.04	1.02	None	-	None	PS001
15	Louisa Bridge TP	7.62	271.8	100.52	29.57	9.04	209.42	413.89	<0.07	16	44.48	0.99	123	Exact	6	PS001
16	Knocknarea Glen W	8.27	282.9	78.22	15.17	1.07	15.34	22.78	0.84	11	6.96	1.08	125	Equiv.	2	PS057
17	Annacoona Waterfall	8.23	260.4	76.96	4.20	0.44	7.17	7.74	0.20	5	6.61	0.98	128	Exact	1	PS058
18	Annacoona Upr Cliffs	8.13	145.7	34.76	6.30	0.37	7.00	8.88	1.34	9	5.84	0.92	129	Exact	8	PS058
19	Cormac Reagh's Hole	8.19	199.1	57.34	5.56	0.66	10.76	13.49	0.39	6	11.91	0.98	132	Exact	5	PS106
20	Annacoona Lwr Cliffs	8.16	170.1	48.32	3.18	0.31	6.69	7.03	<0.07	6	2.75	0.98	133	Exact	8	PS058
21	Benbulbin corrie	8.35	184.3	51.46	4.28	0.41	8.21	9.37	0.81	5	3.14	0.98	135	Equiv.	8	PS107
22	Benwiskin	8.34	150.3	43.16	3.76	0.43	9.56	12.98	0.94	5	5.24	0.98	136	Exact	8	PS108
23	Corhawnagh	7.73	451.0	114.04	19.43	1.95	10.43	18.28	4.53	11	7.19	0.96	104-106	Equiv.	5	PS059
24	Ballycurrin Fen E	7.52	215.5	66.40	3.80	0.27	8.97	13.05	<0.07	3	0.06	1.03	16	Equiv.	5	PS065
25	Ballycurrin Fen W	8.02	332.8	82.78	12.64	0.41	8.62	11.41	<0.07	5	0.31	0.96	92	Equiv.	5	PS065
26	Knocknagur	7.44	147.2	48.60	1.77	0.43	7.54	10.04	1.06	7	5.59	1.03	137	Exact	7	PS063
27	Eskeragh Bridge	7.63	336.1	97.98	9.82	1.35	18.21	27.71	0.07	5	4.74	1.02	95	Equiv.	5	PS030

WS	Location	pH	Alkalinity mg/l HCO_3^-	Ca^{2+} mg/l	Mg^{2+} mg/l	K^+ mg/l	Na^{2+} mg/l	Cl^- mg/l	NO_3^- mg/l	PO_4^{3-} µg/l	SO_4^{2-} mg/l	Ion Balance	QL	QL Note	Fuzzy Cluster	PS
28	Eskeragh Bridge	7.40	328.4	90.24	9.81	0.57	15.65	24.74	<0.07	4	2.40	0.98	96	Equiv.	5	PS030
29	Dooaghtry	7.98	277.0	79.46	9.46	0.83	25.53	37.75	<0.07	4	3.18	1.04	93, 94	Equiv.	Mixed	PS028
30	Dooaghtry (non-quadrat)	7.55	295.7	82.54	7.97	0.98	20.53	30.19	<0.07	4	2.27	0.99	None	-	None	PS028
31	Old Head	8.25	239.3	40.90	24.88	1.22	32.22	55.04	<0.07	4	6.46	0.99	138	Exact	6	PS025
32	Spanish Pt HC	11.38	161.5	66.62	0.22	9.61	62.88	84.21	1.41	11	48.73	1.04	139	Exact	7	PS099
33	Spanish Pt MCHRO	8.14	274.0	94.42	13.26	5.82	57.74	108.35	14.96	6	39.04	0.99	51	Exact	1	PS099
34	Rinnamona Lough FEN	7.76	222.0	67.52	1.10	0.14	5.10	7.65	<0.07	4	<0.06	0.96	89	Equiv	5	PS104
35	Rinnamona Lough SH	7.78	157.1	49.08	1.42	0.43	6.49	7.13	3.11	6	2.41	1.00	87	Exact	6	PS103
36	Glenamannagh LWR	8.06	241.8	74.28	1.89	0.45	8.45	8.26	1.50	4	1.71	1.00	74	Exact	7	PS092
37	Glenamannagh MID	8.13	240.6	71.42	1.81	0.27	7.22	7.81	0.28	5	0.85	0.96	140	Exact	7	PS092
38	Feenagh	7.77	232.3	71.92	1.78	0.82	5.63	8.52	0.88	5	1.04	0.98	15	Exact	4	PS049
39	Cappanawalla NAC	7.49	230.3	71.10	1.57	0.33	5.70	6.98	1.14	4	0.96	0.98	73	Equiv	7	PS093
40	Cappanawalla NAC	7.41	227.4	67.56	1.60	0.44	5.83	7.01	1.08	4	1.08	0.95	65	Equiv	7	PS093
41	Black Head CHS	8.24	187.1	56.76	1.81	0.36	7.56	8.42	0.75	4	1.44	0.99	27	Exact	6	PS084
42	Black Head CTF	8.13	186.4	57.50	1.74	0.39	7.20	8.71	1.01	3	1.53	1.00	28	Exact	1	PS084
43	Black Head CWF	8.31	182.0	54.16	1.66	0.43	6.63	8.45	0.94	4	1.50	0.96	90	Exact	8	PS084
44	Caher River	8.38	239.6	75.74	1.77	0.60	6.70	7.94	0.84	6	1.03	1.01	None	-	None	PS085
45	Slievecarran	7.79	243.5	71.16	2.00	0.38	7.47	7.72	1.72	7	1.72	0.95	71	Equiv	5	PS054
46	Coast N of Skerries MC	7.92	330.6	95.48	15.22	1.98	43.40	72.79	8.22	19	22.68	0.99	154	Exact	1	PS022
47	Coast N of Skerries LB	7.98	304.3	97.86	20.82	1.47	32.50	62.57	44.05	20	33.48	0.99	153	Exact	4	PS022
48	Coast N of Skerries SB	8.01	357.9	107.12	20.46	22.97	46.40	96.46	32.99	21	42.67	0.96	155	Exact	3	PS022

Appendix V: Chemical Composition of Spring Water

WS	Location	pH	Alkalinity mg/l HCO_3^-	Ca^{2+} mg/l	Mg^{2+} mg/l	K^+ mg/l	Na^{2+} mg/l	Cl^- mg/l	NO_3^- mg/l	PO_4^{3-} µg/l	SO_4^{2-} mg/l	Ion Balance	QL	QL Note	Fuzzy Cluster	PS
52	Glenasmole NS	8.06	287.9	83.44	8.33	0.77	7.29	9.46	1.59	27	11.16	0.99	5	Equiv	2	PS015.2
53	Glenasmole SKLC	8.06	290.4	84.78	8.64	0.58	7.74	11.64	5.04	18	10.39	0.99	13	Exact	1	PS015.1
54	Glenasmole SKLL	7.97	237.9	69.34	8.52	0.53	8.01	11.98	4.03	18	10.87	1.00	H	Exact	None	PS015.1
55	Glenasmole YS	8.07	295.7	81.56	10.09	0.31	14.03	21.44	3.30	23	15.01	0.95	37	Equiv	2	PS015.1
56	Glenasmole Upr HR	8.09	306.0	96.50	6.01	1.54	11.10	18.10	2.30	18	11.10	1.01	49	Exact	1	PS014.2
57	Knocksink BARS	8.02	386.3	114.94	8.52	0.74	10.93	12.78	7.98	51	14.30	0.98	29	Equiv	2	PS002
58	Knocksink BM	7.00	644.2	181.22	15.83	6.66	46.82	49.69	5.26	27	20.08	1.01	40	Exact	3	PS002
59	Seven Springs 1D	7.29	358.7	110.02	10.39	1.02	9.18	13.39	12.65	28	16.25	1.00	77	Equiv	6	PS055
60	Seven Springs 2D	7.74	353.8	105.26	9.83	1.32	8.55	12.13	8.84	20	13.91	0.98	None	-	None	PS055
61	Glinsk WB	7.85	329.4	103.72	3.80	0.96	8.92	13.66	3.65	17	6.31	0.99	181	Exact	2	PS008
62	Glinsk EBB	8.07	246.9	77.34	3.41	0.85	9.69	16.77	4.22	20	5.64	0.98	182-183	Equiv	2	PS008
63	Coneyburrow DAM	7.86	285.5	88.64	3.29	0.48	5.91	9.41	0.76	16	4.24	0.99	58	Equiv	2	PS073
64	Coneyburrow CASC	7.86	292.8	94.72	3.37	0.88	5.97	9.09	1.19	16	4.09	1.03	57	Equiv	3	PS073
65	Glinsk OPERT	8.18	208.6	70.08	3.52	1.12	9.31	14.50	3.28	15	6.02	1.05	60	Equiv	2	PS074
66	Ballyman Glen IS	7.13	576.8	170.23	14.11	7.57	22.79	34.18	0.00	10	12.87	1.02	141	Exact	2	PS003
67	Ballyman Glen FEN	8.08	249.4	103.02	8.09	0.49	11.81	24.36	64.70	2	13.57	1.04	120	Exact	6	PS003
71	Glenasmole IS	7.19	372.6	140.21	8.69	0.65	8.19	10.75	<0.07	2	96.25	0.96	None	-	None	PS015
78	Knockree (An Óige) 1LWR	8.25	265.5	78.73	7.21	2.01	10.74	13.27	13.16	23	10.45	0.98	53	Exact	3	PS005
79	Knockree (An Óige) 1UPR	8.02	296.7	89.00	7.49	2.21	10.39	12.94	15.60	23	10.54	0.98	55	Equiv	3	PS005
80	Knockree (An Óige) 2SP	8.01	315.0	89.15	6.18	1.25	12.26	15.21	3.74	25	6.48	0.95	56	Equiv	2	PS005
81	Ardmore Pt MC	8.08	226.7	76.47	9.59	3.93	26.38	43.69	43.50	16	17.97	0.97	216	Exact	1	PS091

WS	Location	pH	Alkalinity mg/l HCO_3^-	Ca^{2+} mg/l	Mg^{2+} mg/l	K^+ mg/l	Na^{2+} mg/l	Cl^- mg/l	NO_3^- mg/l	PO_4^{3-} µg/l	SO_4^{2-} mg/l	Ion Balance	QL	QL Note	Fuzzy Cluster	PS
82	Ardmore Pt HR	8.47	243.3	78.70	30.44	8.62	265.88	258.54	<0.07	4	61.40	1.45	36	Exact	4	PS091
83	Ardmore Pt LR	7.82	444.3	135.34	24.26	1.80	82.31	131.89	<0.07	71	36.32	1.05	34	Exact	1	PS091
84	Glenregan QL	8.02	292.8	90.48	3.60	1.46	6.37	11.02	2.96	14	4.75	0.98	186	Exact	2	PS112
85	Glenregan RHS	7.82	310.9	96.74	3.56	1.43	6.31	11.02	3.32	14	4.84	0.98	186	Comp.	2	PS112
86	Lisduff Fen MID	7.04	484.3	129.36	16.51	6.39	9.86	21.98	8.44	59	8.28	0.95	177	Equiv	5	PS078
87	Lisduff Fen WL	7.34	428.7	119.88	14.26	0.36	9.27	16.85	0.28	31	6.33	0.99	178	Exact	5	PS078
88	Silver River QL	7.94	364.0	108.51	4.78	0.39	6.38	8.43	0.07	9	1.88	0.98	219	Equiv	1	PS013
89	Sliver River RHS	7.69	425.5	130.01	4.16	0.89	5.47	7.17	<0.07	12	5.12	0.97	219	Comp.	1	PS013
90	Glenbarrow LS	8.30	215.7	56.08	6.19	0.98	7.12	10.13	<0.07	13	1.34	0.95	148, PQs	Equiv	4	PS070
91	W of Kilgarrow MC	8.34	320.1	104.95	5.25	0.71	6.00	10.31	1.53	12	3.49	1.06	217	Exact	2	PS101
92	W of Kilgarrow TQL	7.99	293.5	84.50	6.30	0.54	6.62	10.79	2.93	15	4.67	0.96	82	Exact	4	PS101
93	Glenacreawan Lough	7.86	177.6	68.18	2.22	0.39	7.54	11.87	<0.07	11	2.23	1.19	171	Equiv	8	PS111
94	Cliffs of Magho	8.15	109.1	19.08	1.14	0.24	7.26	10.76	<0.07	10	1.20	0.65	218	Exact	8	PS119
95	Arroo Mt. FF	7.93	317.0	114.64	7.17	0.75	11.57	16.89	<0.07	11	18.64	1.13	201	Exact	7	PS114
96	Arroo Mt. FBC	8.38	193.2	52.70	10.32	1.02	10.06	12.44	0.75	12	26.21	0.97	203	Exact	7	PS114
97	Arroo Mt. CSH	8.20	211.5	57.97	10.39	1.00	10.11	12.34	0.56	11	26.71	0.96	202	Exact	4	PS114
98	Eagle's Rock CSH	8.31	147.6	47.42	4.35	0.30	6.33	10.05	0.32	8	5.25	1.07	196	Exact	8	PS113
99	Larganavaddoge CSH	8.25	177.1	59.34	7.92	0.28	8.27	13.38	<0.07	11	6.74	1.16	197	Exact	8	PS115
100	Glenade flush CASC	8.25	226.2	67.84	3.81	0.46	7.50	11.15	0.71	9	8.00	0.96	198	Exact	7	PS040
101	Glenade flush STR	8.04	220.1	70.40	4.06	0.41	7.09	10.75	1.87	12	5.77	1.03	199	Exact	7	PS040

Appendix V: Chemical Composition of Spring Water

WS	Location	pH	Alkalinity mg/l HCO_3^-	Ca^{2+} mg/l	Mg^{2+} mg/l	K^+ mg/l	Na^{2+} mg/l	Cl^- mg/l	NO_3^- mg/l	PO_4^{3-} µg/l	SO_4^{2-} mg/l	Ion Balance	QL	QL Note	Fuzzy Cluster	PS
102	Glencar WDT	8.33	129.6	39.25	3.12	0.42	13.90	21.36	2.58	9	5.19	0.98	195	Exact	2	PS038
103	Moneyduff Wood TOP	8.10	337.7	66.38	26.97	1.25	9.62	15.56	2.20	12	8.28	0.97	191	Exact	2	PS039
104	Moneyduff Wood FLU	8.10	339.6	65.56	27.26	1.29	9.11	15.18	2.35	13	7.96	0.96	192	Exact	4	PS039
105	Moneyduff Wood STR	8.03	387.7	77.78	29.13	1.22	8.69	14.61	3.12	15	8.23	0.96	193	Exact	2	PS039
106	Ballincar MC	8.07	303.0	92.40	12.59	3.42	24.78	33.06	16.61	15	38.03	0.98	108	Exact	2	PS036
107	L. Derravarragh TUF	7.92	355.0	107.66	8.15	0.52	8.72	14.41	4.80	16	8.88	0.99	162	Exact	6	PS061
108	L. Derravarragh SCH	7.51	327.9	125.57	6.52	0.54	10.83	17.91	<0.07	15	1.02	1.23	163	Exact	6	PS061
109	L. Derravarragh TOP	7.59	296.5	114.67	7.74	0.67	9.48	17.09	<0.07	15	4.33	1.25	164	Exact	6	PS061
110	Dysart	7.97	241.6	66.32	8.85	0.29	6.96	14.67	3.48	17	6.98	0.95	38	Equiv	1	PS047
111	Kiltown	7.69	405.3	124.23	7.12	0.95	12.75	24.02	5.46	13	9.56	0.97	167	Equiv	3	PS110
112	King's Bog	7.57	385.5	84.19	25.09	1.23	7.37	13.79	8.01	18	14.65	0.93	19	Exact	6	PS044
113	Pollardstown Fen N CSH	7.33	403.6	85.67	27.46	0.87	8.12	15.57	5.70	16	18.74	0.92	206	Exact	4	PS004.2
114	Pollardstown Fen N 1QL	7.54	362.6	79.71	29.28	3.06	8.14	17.29	16.60	20	18.50	0.96	32	Exact	6	PS004.2
115	Pollardstown Fen N TRK	7.76	431.4	103.48	22.58	1.26	8.24	17.47	19.02	17	16.73	0.90	33	Equiv	6	PS004.2
116	Pollardstown Fen SW	7.39	345.0	102.79	5.12	0.16	7.61	11.00	<0.07	7	3.25	0.98	204	Exact	6	PS004.3
117	Pollardstown Fen SE	7.59	356.5	94.17	15.39	0.16	11.02	19.48	<0.07	9	13.81	0.97	207	Exact	5	PS004.1
118	Hartwell Upr STRH	7.32	404.8	121.32	10.61	0.78	8.68	16.56	15.20	20	18.67	0.95	99	Equiv	4	PS045
119	Hartwell Upr FSEEP	7.95	337.5	92.34	9.41	0.97	7.96	16.71	0.65	29	9.43	0.93	100,101	Equiv	6	PS045
123	Ballynafagh	7.24	345.3	109.72	11.22	1.69	8.28	25.80	<0.07	13	23.82	0.99	85	Equiv	5	PS016
127	Broadboyne Bridge	7.90	475.6	148.09	6.41	4.63	13.51	24.43	28.43	66	16.22	0.93	21	Exact	3	PS032

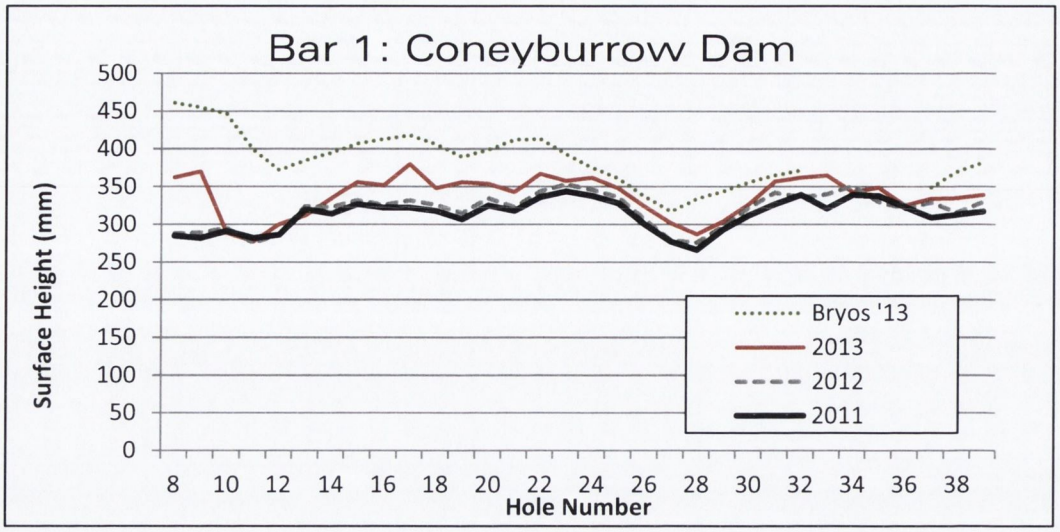
WS	Location	pH	Alkalinity mg/l HCO_3^-	Ca^{2+} mg/l	Mg^{2+} mg/l	K^+ mg/l	Na^{2+} mg/l	Cl^- mg/l	NO_3^- mg/l	PO_4^{3-} µg/l	SO_4^{2-} mg/l	Ion Balance	QL	QL Note	Fuzzy Cluster	PS
128	Rathcor E	7.69	359.4	118.94	10.61	3.04	20.90	31.89	35.66	14	26.63	0.98	213	Exact	1	PS118
129	Rathcor W	7.64	360.4	115.70	10.91	10.40	31.05	40.26	34.22	14	26.59	1.02	214	Exact	4	PS118
130	Carlingford Marina	7.94	187.1	50.92	4.73	1.02	12.69	15.10	6.79	8	5.20	0.95	160	Exact	4	PS017
131	Marconi's Cottage	8.14	222.0	54.06	20.84	3.11	26.67	41.16	1.59	10	51.40	0.96	210	Exact	4	PS117
132	Murlough Bay STR	8.30	304.0	95.71	3.13	0.74	12.50	18.86	4.08	36	5.42	0.98	209	Exact	3	PS116
133	Balscadden Beach	8.25	199.8	56.01	18.93	1.92	53.24	81.60	10.38	16	48.01	1.00	83	Equiv	1	PS076
134	Kilrock Quarry BW	7.98	207.9	55.13	18.62	2.01	50.31	85.55	<0.07	11	45.07	0.96	165	Exact	6	PS021
135	Kilrock Quarry FLU	7.19	192.8	56.99	17.24	3.02	59.00	94.88	<0.07	14	57.20	0.98	166	Exact	8	PS021
136	Howth (off Upr Cliff Rd)	7.31	385.0	108.37	15.06	0.89	49.48	70.39	<0.07	16	21.51	1.01	84	Exact	6	PS048
137	Liffey Valley (S side) SEEP	7.91	327.7	147.20	11.30	3.22	53.92	83.01	5.09	140	146.88	0.99	156	Exact	3	PS018
138	Liffey Valley (S side) STR	7.82	323.5	143.08	11.11	3.28	54.19	82.73	5.48	115	142.22	0.98	157	Exact	3	PS018
139	Liffey Valley (N side) POND	8.09	300.4	97.77	7.02	3.02	20.56	33.91	2.68	991	29.24	0.98	159	Exact	3	PS109

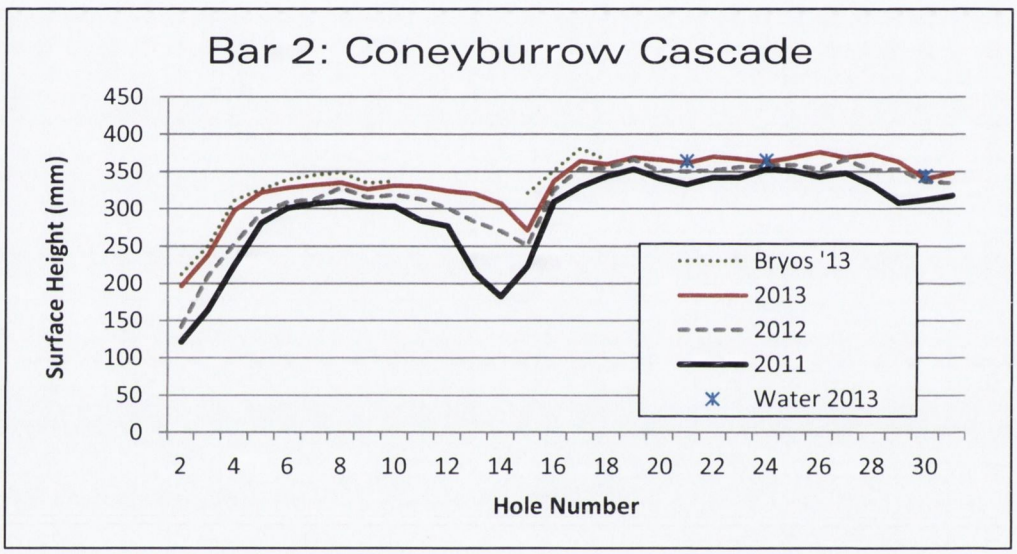
WS Water sample reference number

QL Relevé (quadrat) reference number

QL Note Exact: water sample collected inside quadrat;
Equiv: water sample equivalent to quadrat (collected close-by)
Comp: additional sample collected for comparison purposes

Fuzzy Cluster Plant community to which corresponding relevé was assigned (Groups 1 - 8, Chapter 3)

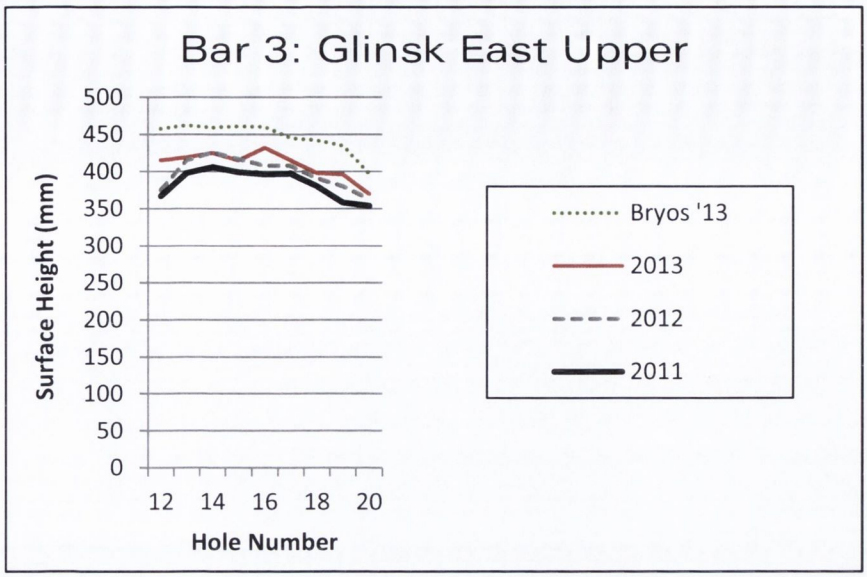


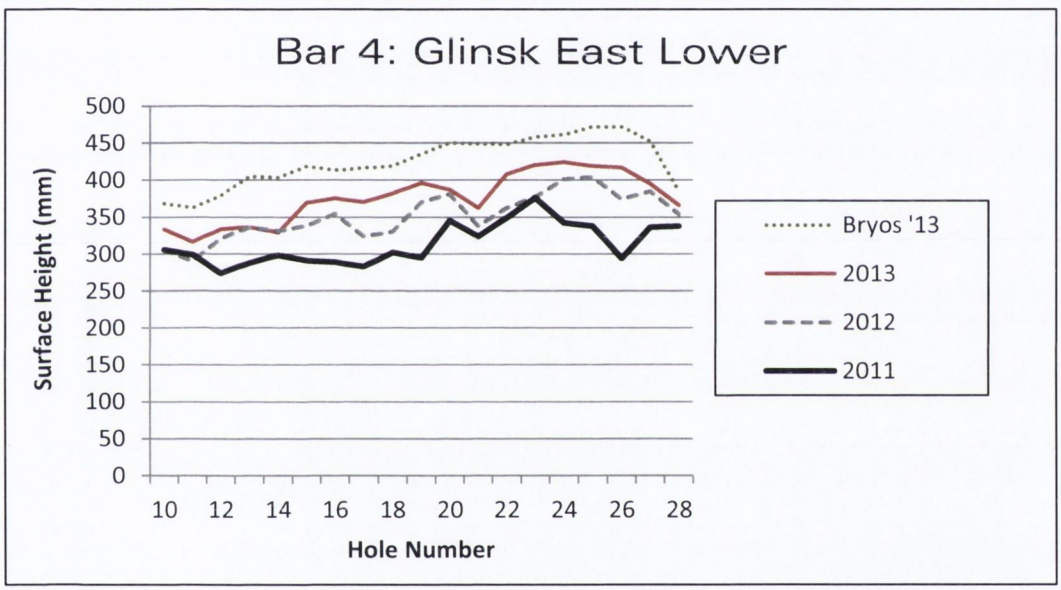


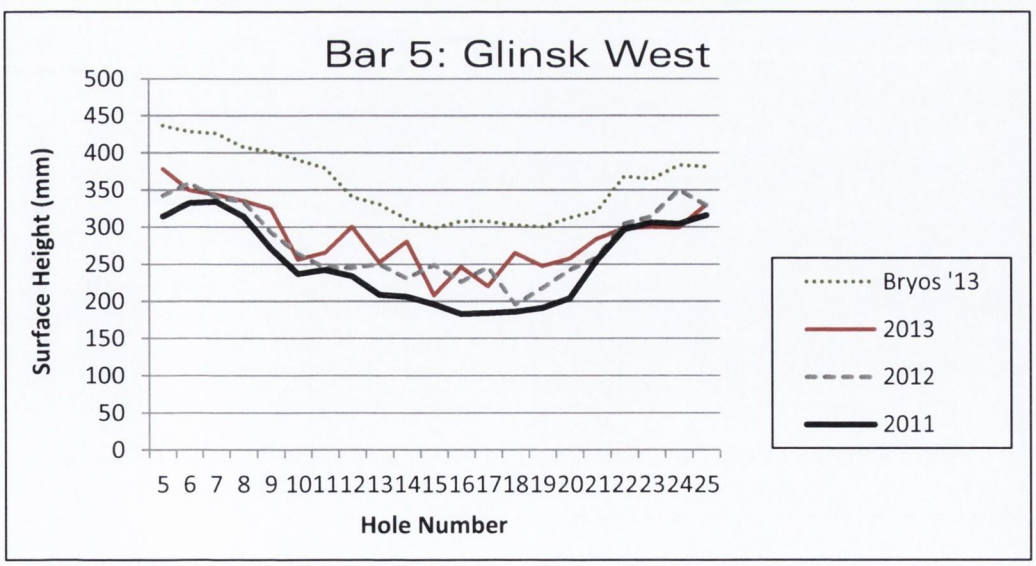
Appendix VI: Profiles of tufa depisits

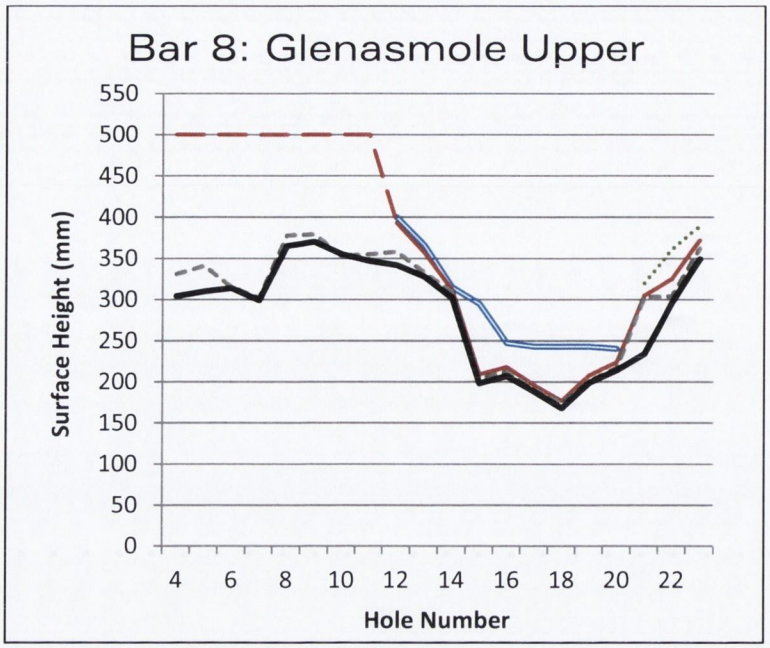
See Chapter 7 for details.

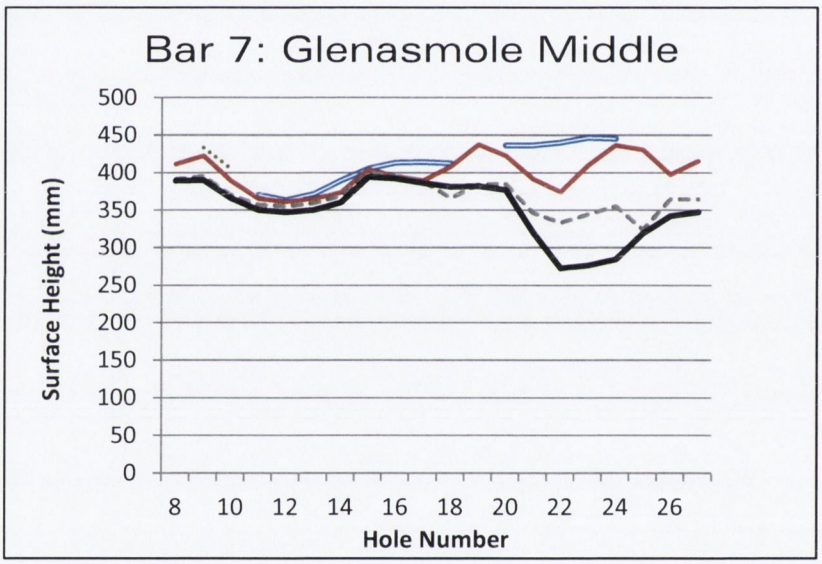
Except where otherwise indicated, curves represent surface level of deposits,
(*i.e.* resting position of rod) for three successive annual measurements (2011 - 2013).
'Bryos' = Bryophytes, *i.e* . the level at which rod first made contact with living bryophyte shoot.
Bryophytes and water, where present, are shown only for the final year of measuring (2013).

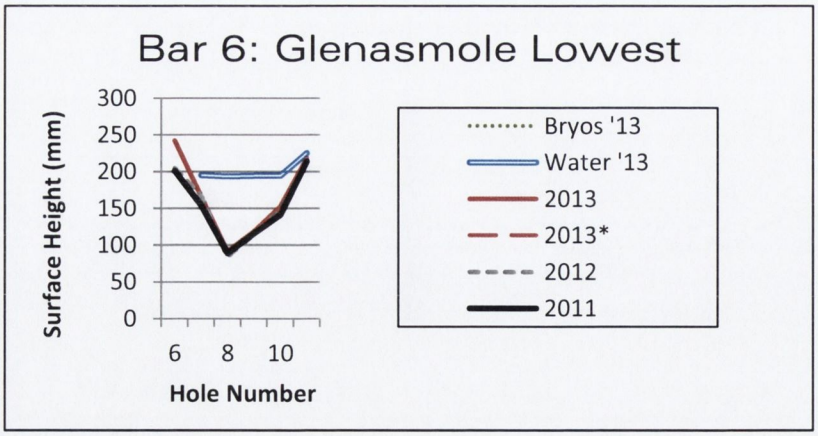

Bar 3: Glinsk East Upper
Surface Height (mm)
500
450
400
350
300
250
200
150
100
50
0
12 14 16 18 20
Hole Number
Bryos '13
2013
2012
2011


Bar 4: Glinsk East Lower
Surface Height (mm)
500
450
400
350
300
250
200
150
100
50
0
10 12 14 16 18 20 22 24 26 28
Hole Number
Bryos '13
2013
2012
2011

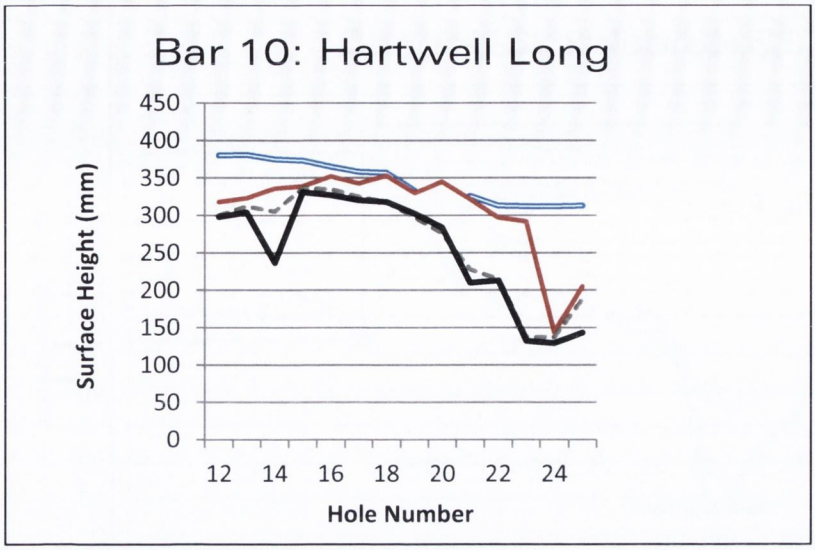

Bar 5: Glinsk West
Surface Height (mm)
500
450
400
350
300
250
200
150
100
50
0
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Hole Number
Bryos '13
2013
2012
2011

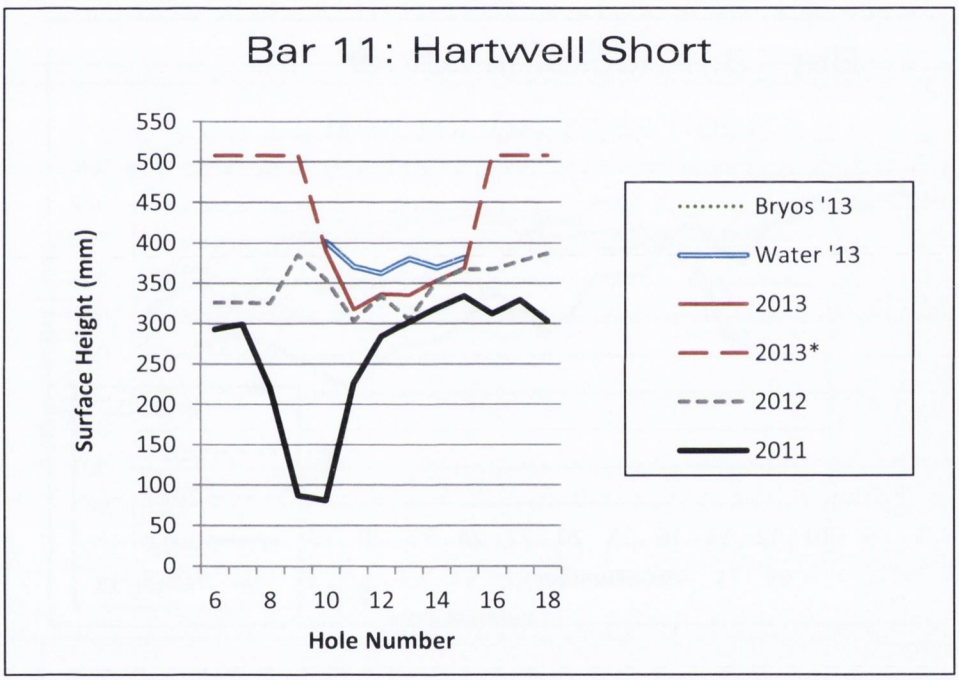






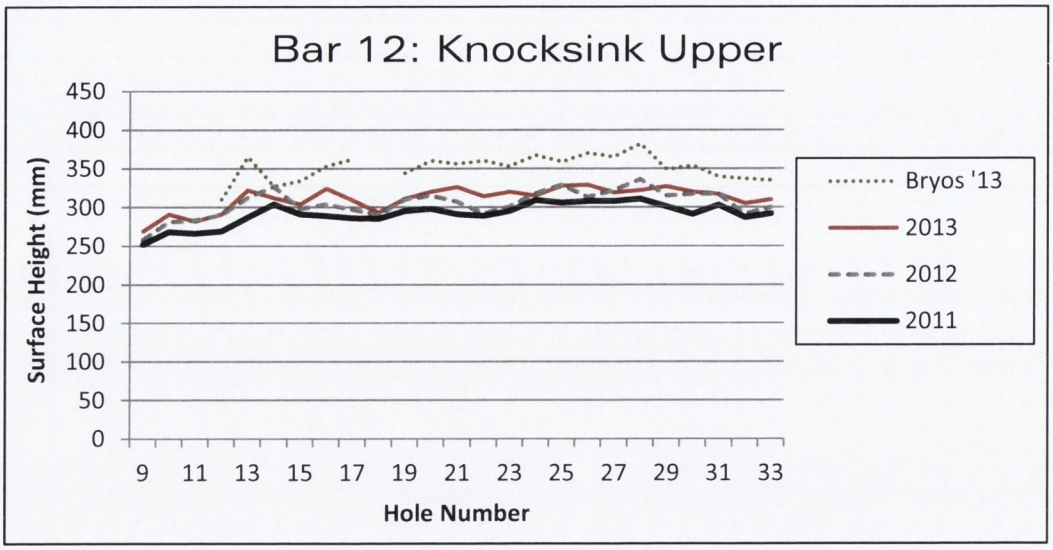
* Tufa overtopped bar; measurements excluded from calculations

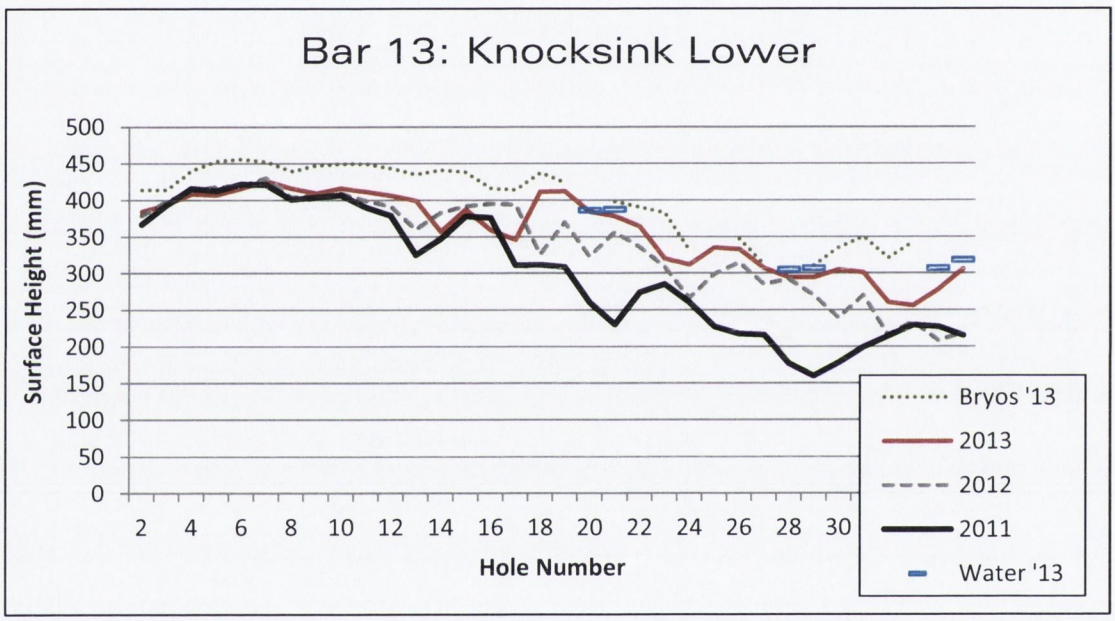


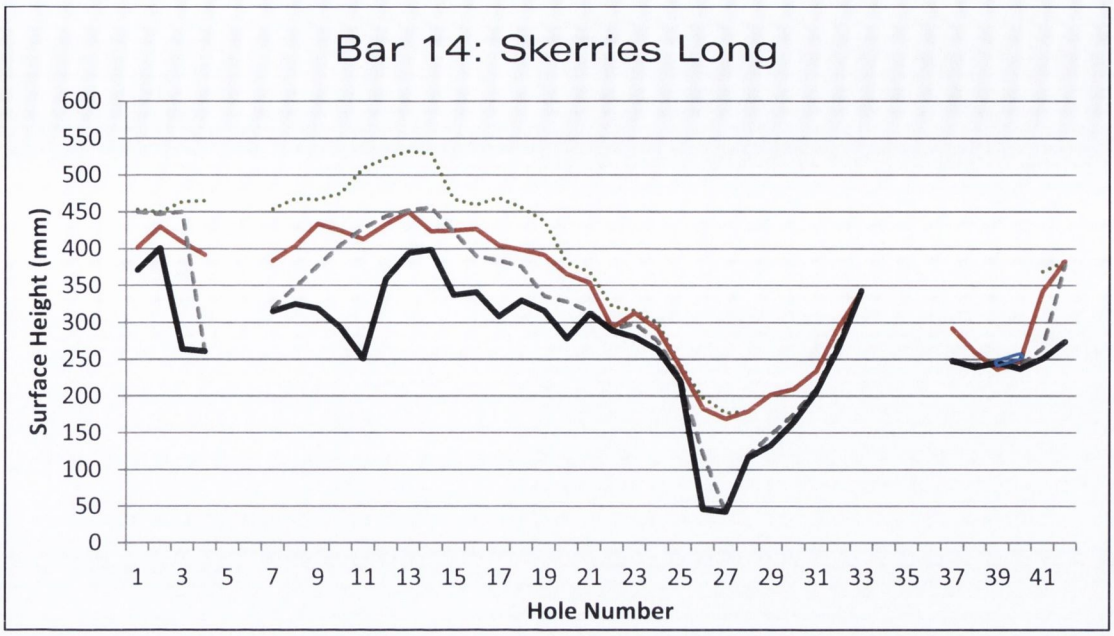


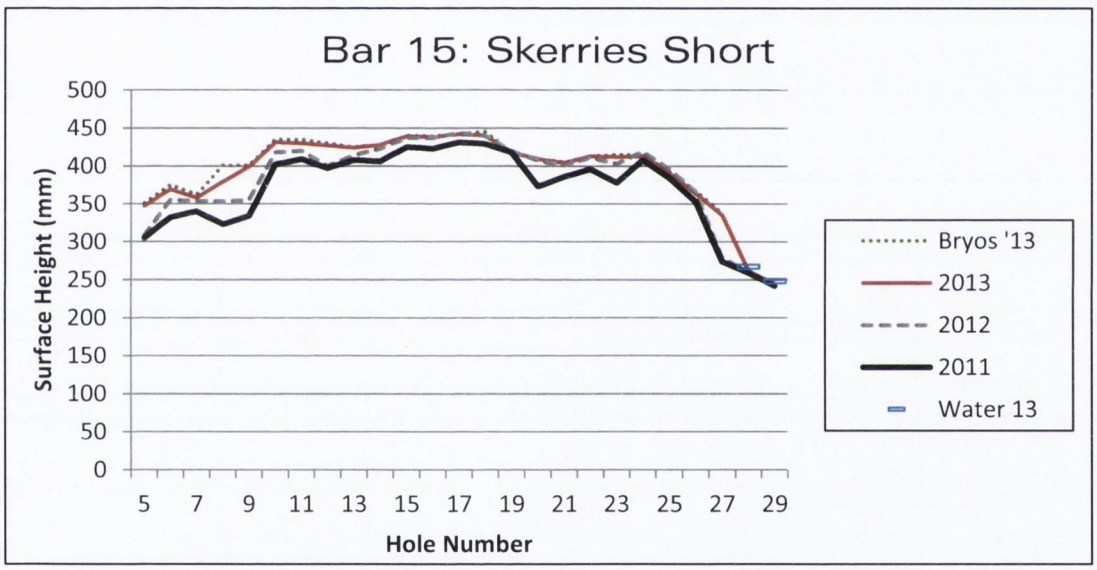
* Tufa overtopped bar; measurements excluded from calculations.

(Bar 9 was unstable due to its length and was not used for making measurements.)


Bar 12: Knocksink Upper
Surface Height (mm)
450
400
350
300
250
200
150
100
50
0
9 11 13 15 17 19 21 23 25 27 29 31 33
Hole Number
Bryos '13
2013
2012
2011


Bar 13: Knocksink Lower
Surface Height (mm)
500
450
400
350
300
250
200
150
100
50
0
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Hole Number
Bryos '13
2013
2012
2011
Water '13





Gaps in curves for Bar 14 are locations of supporting threaded bars.
(See Section 7.1.1 and Photo 7.3)

PETRIFYING SPRINGS 2 x 2m QUADRAT		QL
Spring Ref: PS	**Date:**	**Relevé location:**
Site Name:		
Spring Name:		
Grid Ref:	± m	
Start Time:	**Altitude:** m	
End Time:	**Aspect:**	
Surveyor(s):	**Slope:**	
❑ 2x2m ❑ 1x4m ❑ Irregular	Hom 1 2 3 4 5 Het	
❑ Spring Head ❑ Flush	❑ Other:	
pH EC µS	Temp. °C	

Tufa (% of quadrat, inc. below veg/water)		**Water** (% of quadrat surface)		**Surface** (% quadrat, visible, excl. water)	
❑ Cascade	%	❑ Flowing / stream	%	❑ Living field / ground flora	%
❑ Paludal / dispersed 1 2 3	%	❑ Slow movement / trickling	%	❑ Bare tufa (active/recent)	%
❑ Stream crust	%	❑ Pool / standing water	%	❑ Ancient / inactive tufa	%
❑ Oncoids / ooids	%	❑ Dripping	%	❑ Leaf litter	%
❑ Dam	%	❑ Damp	%	❑ Bare soil	%
❑ Mound	%	❑ Dry, not impacted by spring	%	❑ Bare stone	%
❑ Cemented rudites / clasts	%	❑ Iron oxide	%	❑ Other	%
❑ Non-tufa	%	❑ Other	%	❑ Other	%
TOTAL 100	%	**TOTAL** 100	%	**TOTAL** 100	%
❑ **Tufa sparse or absent** ❑ Absent	❑ Trace (on ground)	❑ Trace (on plants)	❑ Other:		

Paludal tufa 1= weak/thin/discontinuous, 3 = strongly forming/continuous/conspicuous *Cover values: record to nearest 5%. If <5%, then use: 3%, 1%, 0.5%, 0.1%*

Field / Ground Flora

✓	FORBS	%	✓	GRAMINOIDS	%	✓	BRYOPHYTES	%	✓	WOODY (<50cm)	%
❑	Anagallis tenella		❑	Agrostis stolonifera		❑	Aneura pinguis		❑	Acer pseudoplatanus	
❑	Cardamine pratensis		❑	Briza media		❑	Brachythecium rivulare		❑	Fraxinus excelsior	
❑	Cirsium palustre		❑	Carex flacca		❑	Bryum pseudotriquetrum		❑	Hedera helix	
❑	Crepis paludosa		❑	Carex lepidocarpa		❑	Calliergonella cuspidata		❑	Salix cinerea	
❑	Epilobium parviflorum		❑	Carex panicea		❑	Campylium stellatum		❑		
❑	Geranium robertianum		❑	Carex remota		❑	Cratoneuron filicinum		❑		
❑	Hypericum tetrapterum		❑	Festuca rubra		❑	Didymodon tophaceus		❑		
❑	Mentha aquatica		❑	Juncus articulatus		❑	Eucladium verticillatum		❑		
❑	Nasturtium officinale		❑	Juncus inflexus		❑	Fissidens adianthoides		★	**TOTAL WOODY <50cm**	
❑	Pinguicula vulgaris		❑	Poa trivialis		❑	Palustriella commutata				
❑	Ranunculus flammula		❑	Schoenus nigricans		❑	Pellia endiviifolia		✓	**OTHER**	%
❑	Ranunculus repens		❑			❑	Philonotis calcarea		❑	Equisetum telmateia	
❑	Succisa pratensis		❑			❑	Pohlia wahlenbergii		❑		
❑	Veronica beccabunga		❑			❑	Scorpidium cossonii		❑		
❑			❑			❑			❑		
❑			❑			❑			❑		
❑			❑			❑			❑		
❑			❑			❑			❑		
❑			❑			❑			❑		
❑			❑			❑			★	**TOTAL PTERIDOPHYTES**	
❑			❑			❑			★	**TOTAL ALGAE**	
★	**TOTAL FORBS**		★	**TOTAL GRAMINOIDS**		★	**TOTAL BRYOPHYTES**		★	**TOTAL LICHENS**	

❑ *Add other species overleaf...*

Additional Ground Flora Species			
SPECIES	%	SPECIES	%

Shrub / Canopy Layer			
SPECIES	Rooted outside % Canopy	Rooted inside % Canopy	Rooted inside (max) Height Class
TOTAL CANOPY (ROOTED INSIDE + OUTSIDE) %	Total %	Total %	
MAX HEIGHT CLASS ABOVE QUADRAT (ROOTED INSIDE + OUTSIDE):			

Height Classes: S =shrub/sapling (≥50cm,<2m) C1=≥2,<4m, C2=≥4,<8m, C3=≥8,<12m, C4=≥12,<16m, C5=≥16m

Water Samples										
WS Ref:										

NOTE

Appendix VIII: Tufa deposits at Hartwell, Co. Kildare.

This is a remarkable site that includes (upslope from, and adjacent to, the contemporary depositional sites) very extensive tufa deposits that are no longer active. Dr Pete Coxon, TCD, accompanied me on a site visit in June 2013 and we estimated (by sampling at intervals with an auger) that several hectares of present-day pasture land are underlain by fossil tufa. Such tufa drapes on landscapes are rare on such a scale but not unknown (Preece *et al.* 1986) and can represent accumulation that has occurred throughout the Late-Glacial and Holocene. The Hartwell deposits are thick (*c.* 5m in places) and, whilst their age is unknown, they probably represent accumulation (spatially and temporally variable) throughout the Holocene (P. Coxon pers. comm.).

Ancient, inactive deposits have been quarried in the past (Photo 9.2). A small church is located on a neighbouring estate, Furness (or Forenaghts Great), 1.5km south-west of the quarry site and part of its structure consists of dressed tufa (Photos 9.1 and 9.3). Details of arches, windows and cornerstones are made of tufa. Written evidence shows the church to have been founded by 1210, but some features of its construction and a large granite tombstone are indicative of an earlier date, not later than mid-7th Century (Synnott 1969).

On a separate trip to Hartwell to collect water samples in September 2012, I was accompanied by some members of the BBS who were recording bryophytes in Kildare at that time. Nick Hodgetts found the leafy liverwort *Lophozia personii* on an upturned tree plate close to the tufa cascade. This was the first time this species had been found in Ireland (it is not associated with tufa formation at the site).

I am grateful to my aunt, Mabel Lyons, for bringing the site to my attention; I found no reference to it elsewhere in the literature on petrifying springs.



Photo 9.1: Window framed by tufa at Furness church (May 2012).



Photo 9.2: Ancient tufa deposits at Hartwell (June 2012) which have been quarried in the past. See Photos 3.17 and 6.9 to 6.12 for active tufa deposits.



Photo 9.3: Church at Furness, 1.5km SW of the deposits shown in Photo 9.2 above, with dressed tufa decorating the central arch (May 2012).