SPATIAL AND TEMPORAL FLUXES OF PLANT-NUTRIENTS IN TURLOUGH SOILS

Presented in fulfilment
of the requirements for the degree of
Doctor of Philosophy
May 2008

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For Mum, Dad and Dorothy.

DECLARATION

This thesis has not been submitted for a degree to this or any other university and, with acknowledged exception, is entirely my own work.

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SUMMARY

Turloughs are annually flooding karstic depressions which constitute ecologically important and geographically restricted ground-water dependent ecosystems, identified as priority habitats under the EU Habitats Directive. Turlough conservation is also driven by the EU Water Framework Directive and recent developments have attempted to characterise the karst aquifers associated with turloughs, which are generally of a conduit or shallow epikarst nature. Different types of karst aquifers are thought to account for ecological diversity among turloughs and influence turlough trophic status, which is currently assessed using qualitative assessments of the proportional area of nutrient-sensitive plant communities. The natural trophic status of turloughs is also thought to be influenced by the soil types present, however the relationships between turlough karst aquifers, soil types and soil nutrient status are poorly understood. Eutrophication constitutes one of the main threats to the quality of the turlough habitat and soil nutrient assessments are required as part of the current drive to generate quantitative information on turlough trophic ranges. Soil property variability is well recognised, however information on the spatial and temporal variations of soil nutrient related properties, and how these might influence plant community structure and sampling strategies for conservation assessment, is lacking. The primary aim of this project is to contribute to a better understanding of turlough spatial and temporal soil nutrient dynamics and their associations with soil types, vegetation types, karst aquifer types and current turlough trophic assessments at both catchment and within-turlough scales.

At the catchment scale, focus was placed on determining whether turloughs located within different types of karstic flow systems have contrasting soil nutrient properties. The implications of spatial within-site variation for making soil nutrient comparisons among turloughs located in the same catchment were also investigated. The variation in nutrient properties within and among soil types characteristic of each catchment were examined, along with the relation between vegetation communities and soil nutrient properties. Four turloughs were selected for study from the conduit flow system associated with the Coole Garryland SAC, Co. Galway and four were selected from the shallow epikarst flow system within the East Burren SAC, Co. Clare. Soil types and nutrient related properties were described in the upper, middle and lower areas of each turlough. Mineral, moderately calcareous soils were associated with Coole Garryland whereas highly organic, highly calcareous soils were characteristic of the East Burren. This variation in soil types was attributed to the contrasting parent materials, hydrology and hydrochemistry associated with the different types of karst aquifers within each catchment area. The general N, P and K status of the two catchments was low, which was in agreement with previous trophic assessments of turloughs as low nutrient habitats which are sensitive to enrichment.

Marginally higher (total and available) phosphorus and potassium concentrations were associated with Coole Garryland, which reflected the relatively more eutrophic assessment of turloughs in this catchment. Sampling location was found to be an important factor when making comparisons of pH and Morgans P among turloughs in Coole-Garryland, whereas sampling location was found to influence Total N, P, Ca and plant available forms of P in comparisons among turloughs in the East Burren catchment. This suggests that spatial variability presents a greater challenge for making soil nutrient comparisons among turloughs in the East Burren. High degrees of variation were generally associated with the turlough soil types characteristic of each catchment. Kilcolgan Series Rendzinas and Gleys were characteristic of Coole Garryland whereas Burren Series Rendzinas, Fen Peats, and Marls were characteristic of the East Burren. Such variation presents challenges for making nutrient comparisons among turlough soils types and potentially for detecting true relationships between soil types, vegetation and hydrology. Soil nutrient conditions were found to be a secondary influence to degrees of wetness and associated soil alkalinities on the distributions of grass/forb dominated vegetation types and sedge dominated vegetation types.

At the within-turlough scale, more detailed investigations of the spatial patterns of plant-nutrient availablity, and their relation to soil type and flooding susceptibility, were conducted using gradient directed transects within two turloughs representative of each catchment. High degrees of variation in plant-nutrient availability were associated with the turlough flooding gradients and spatial patterns were often not obviously linked to soil type. Soil moisture conditions at the time of sampling are likely to exert a greater influence than soil type on soil nutrient status at any given location in a turlough, particularly in lower turlough areas. Different soil properties varied to different extents within different turloughs, indicating that accurate mean soil nutrients will be readily estimated for some properties more than others in different turloughs. The temporal variations (monthly) in nutrient availability among common turlough soil types were also considered within selected turloughs representative of each catchment, along with the implications of temporal variations for making soil nutrient assessments of individual turloughs. Temporal trends in plant-available forms of N and P differed among the Rendzinas, Gleys and Peats, suggesting that contrasting nutrient cycling dynamics were associated with these different soil types. Mean nutrient assessments based on plant-available P consistently reflected an oligotrophic and ultra-oligotrophic nutrient status within Garryland and Knockaunroe respectively over the growing season whereas mean nutrient assessments based on plant-available N varied among sampling periods. The results presented in this thesis suggest that the spatial and temporal fluxes of nutrients in turlough soils present challenges for making accurate soil nutrient assessments and understanding turlough soil nutrient cycling and highlight the requirement for sampling strategies which cover the range of variation within the turlough basin.

ACKNOWLEDGEMENTS

First of all, I would like to sincerely thank Dr. Steve Waldren for introducing me to turloughs and for his guidance and encouragement throughout this project. I am also deeply grateful for his continued support and faith in me.

Thanks also to the Environmental Protection Agency for providing the generous project funding.

I would also like to thank Dr. Norman Allott, Dr. Louise Scally and Mark Kavanagh for their management of the laboratory used for this project and for their advice on numerous laboratory analyses. I am also very grateful for analytical advice received from Dr. David Styles, Dr. Eddy Minet, Siobhan MacNamee and Antoin Lawlor.

I am also indebted to all those in the Centre for the Environment and the Botany Department (especially in Room 9) for helping me to maintain my sense of humour. A very special thanks goes to Dr. Noeleen Smyth for being such a great friend, above all thanks for the listening, laughing and practical advice.

A special thanks to Jennifer, Sinead, Rhoda and Cait for not mentioning it.

Most importantly, I am deeply appreciative, now and always, of the love and support of my Mum, Dad and sister Dorothy. Thank you for helping me, in so many ways, to complete this thesis.

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ABBREVIATIONS

Abbreviation	
A	Alluvium
ANOVA	Analysis of variance
BAP	Biodiversity Action Plan
CG	Caherglassaun turlough, Co. Galway
$CaCO_3$	Calcium carbonate
Ca_{ex}	Exchangeable calcium
Ca_t	Total Calcium
CE	Inse woods turlough, Coole Co. Galway
CO	Cooloorta turlough, Co. Clare
CR	Lough Cuil Reasc turlough, Co. Clare
CV	Coefficient of variation
EPA	Environmental Protection Agency
Fe_{ox}	Oxalate extractable iron
Fe_t	Total iron
FP	Fen Peat
G	Gley
GD	Garryland turlough, Co. Galway
GT	Gortlecka turlough, Co. Clare
GWDTE	Groundwater Dependent Terrestrial Ecosystem
HH	Hawkhill turlough, Co. Galway
KE	Knockaunroe turlough, Co. Clare
K_{ex}	Exchangeable potassium
K_t	Total potassium
M	Marl
Mg_{ex}	Exchangeable magnesium
Mg_t	Total magnesium
NH_4^+-N	Ammonium-nitrogen
NO_3^--N	Nitrate-nitrogen
N_t	Total nitrogen
N_{tin}	Total inorganic nitrogen
NHA	Natural Hertitage Area
NPWS	National Parks and Wildlife Service
OM	Organic matter
P_{feo}	Desorbable phosphorus
PM	Peat-Marl
P_m	Morgans Phosphorus
P_{ox}	Oxalate extractable phosphorus
P_t	Total phosphorus
P_w	Water extractable phosphorus
RBS	Burren Series Rendzina
RKS	Kilcolgan Series Rendzina
SAC	Special Area of Conservation
SPA	Special Protection Area
SM	Soil moisture
TEB	Total exchangeable bases
WFD	Water Framework Directive

CHAPTER 1. GENERAL INTRODUCTION

1.1 Wetland conservation

Wetlands exhibit a high degree of natural variation which is evident in their description under the Ramsar Convention (The Convention on Wetlands of International Importance especially as Waterfowl Habitat), adopted in 1971 (Ramsar Convention Secretariat, 2004) where they are defined as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or saline, including areas of marine water the depth of which at low tide does not exceed six meters". The main challenges of wetland conservation, as outlined by Williams (1990), stem from that fact that these variable habitats are generally intermittent in their occurrence and often represent successional stages or transitional zones in a constant state of flux. In Europe, approximately 66% of the wetland area has been lost since the beginning of the twentieth century (EC, 1995) and Irish wetlands, such as saltmarshes, callows, peatlands and turloughs (Otte, 2003), have been negatively impacted by activities such as arterial drainage, intensive agriculture, pollution and development pressure (Cabot, 1999; Stapleton, 2000). Negative attitudes towards wetlands have been reversed however over the past two decades and it is now recognised that they have fundamental landscape ecological functions as regulators of water regimes and as habitats supporting a rich biodiversity (Niering, 1985; Odum, 1996). Much of wetland conservation is now focussed on restoration of natural wetlands and sound management of those that remain, both of which require science-based understanding of wetland functions, such as nutrient cycling.

1.2 Turloughs

1.2.1 General description and origins

Turloughs or temporary limestone lakes have recently been classified as Ground Water Dependent Terrestrial Ecosystems under the Water Framework Directive (2000/60/EC), where they are described as topographic depressions in karst which are intermittently inundated on an annual basis, mainly from groundwater, which lack a surface outflow and have a substrate and/or ecological communities characteristic of wetlands (Working Group on Groundwater, 2004). The majority of turloughs are purely fed by groundwater. However, some have surface water inputs but in these cases the majority of floodwater volume is from groundwater . The hydrological regime of turloughs is dictated by local weather conditions but generally, the basins fill to maximum levels between October and April, are often dry in May and June, and may be variably wet from July through to September (Coxon 1986; Goodwillie and Reynolds, 2003) (plate 1.1).

Goodwillie (2001) states that turloughs intergrade with fluctuation limestone lakes and a convenient if artificial distintinction is turlough winter floodwaters inundate at least double the flooded area during dry summer periods whereas lakes inundate a similar area. The basins flood via porous parts of the basin floor and also via open connections to groundwater known as swallow holes or estavelles (Goodwillie, 1992) and drain, often via the same channels through which they flood, when the water Table is lowered (Goodwillie, 2001) (Plate 1.2). Reynolds (1996) considers that turloughs are more similar to ecotones, which constitute transition zones between aquatic and terrestrial systems, rather than ecosystems. They may be thought of as the shores of underground lakes and can be considered an interface between three different ecological systems; terrestrial, surface water and groundwater, defined by temporal and spatial gradients (Goodwillie, 2001). Pinay *et al.* (1990) consider an ecotone to be a functional entity uniquely defined by space and time scales and emphasise that it is essential to document and understand the dynamics of ecotones, such as turloughs, over various spatial and temporal scales to fully understand their functioning as a wetland.

Most wetlands are relatively young in geological terms as the majority are of Pleistocene or Holocene origin (Hejny and Segal, 1998). The geological origin of turloughs has been the source of considerable discussion (Coxon, 1986) and to date the issue remains unresolved, however it is agreed that an explanation for the origin of turloughs must account for the formation of a closed basin and the existence of a narrow zone of higher permeability. Turloughs tend to occur in glacial depositional landscapes (Coxon, 1987) and if the closed basin was glacially scoured it was likely to have occurred in glaciations prior to the last one. If the closed basin was formed by solutional processes this would also place turlough origins in preglacial times as these processes are extremely slow. These karstically formed depressions may be subsequently modified by glacial erosion and deposition (Coxon, 1986). A critical conclusion from the geomorphological aspects of studies conducted by MacGowran (1985) and Coxon (1986) was that the presence of marl in the sedimentary record suggests that most turlough basins were permanent lakes towards the end of the Pleistocene and that the period upon which they became seasonal is unknown (plate 1.3). Many turloughs however have peat in the sedimentary profile and lack marl, indicating previous conditions for peat formation and the absence of a permanent lake (MacGowran, 1985) or conditions in a lake not conducive to marl deposition. Overall, the dynamics of turlough hydrology are poorly understood but it is accepted that the hydrology of many turloughs changes naturally throughout their existence (Goodwillie and Reynolds, 2003) with shifts caused by changes in the drainage systems of the underlying rock or bottom sediments as swallow holes and fissures become open or blocked by marl depositions (Goodwillie, 1992).

Plate 1.1: Garryland turlough May 2004 (above) and September 2004 (below).

Plate 1.2: Swallow hole in Inse woods turlough, Coole Lough, Co. Galway.

Plate 1.3: Evidence of marl in a substrate profile in Caherglassaun turlough. A tent peg provides an indication of scale.

1.2.2 Geographical distribution

Turlough ecotone function requires an infrequently occurring combination of low-lying limestone and wet climate (Drew 1990, 1992) and the greatest global density of this habitat type is found in central and western Ireland (Coxon, 1987) (Figure 1.1). The majority of the 70 turloughs currently designated as SACs and NHAs occur across 14 catchment areas extending from Co. Donegal to Co. Clare. They are predominantly low-level features: the highest is the Loughans, Co. Kilkenny at 129 m, ten metres above that at Carran, Co. Clare (Southern Water Global, 1998). A broad belt of turloughs extends eastwards from Loughs Corrib and Mask, linking with others in Co. Roscommon west of Lough Ree. Another cluster occurs at the head of Galway Bay and south-westwards into Co. Clare. A few isolated examples are found in Co. Donegal, Co. Sligo, south Co. Clare, Co. Limerick, Co. Tipperary, Co. Kilkenny, Co. Cork and Co. Kerry (Southern Water Global, 1998). Three turloughs have also been identified in Co. Fermanagh, Northern Ireland (UK BAP, 1998). The absence of turloughs from some areas of suiTable bedrock is thought to be due to thick or impermeable glacial drift (Coxon, 1987).

Coxon (1987) suggests that turlough distribution in Ireland is most strongly controlled by the occurrence of Dinantian pure bedded limestone (Figure 1.1), which is highly susceptible to karstification, and shallow (or absent) deposits of diamicton. This combination of factors is well represented in the western third of the country. A comprehensive assessment of the association between turloughs and glacial diamicton was conducted by Coxon (1986). Coxon (1987) noted that the 90 turloughs > 10 ha occur on three of the diamicton categories on the glacial diamicton map in the Atlas of Ireland (Royal Irish Academy, 1979): 63 occur on or adjacent to areas of little or no diamicton cover, 22 occur on sands, gravels and gravely diamicton and five occur on diamicton mainly from Carboniferous limestone. The turlough inventory conducted by Coxon (1986) included information on the main soil associations in the surrounding areas where turloughs occur and concluded that turloughs occur on, or partly on, twelve of the 44 soil associations on the Soil Map of Ireland (Gardiner and Radford, 1980). Table 1.1 shows the five soil associations on which turloughs are frequent. It can be seen that the majority of turloughs occur in areas where the principal soils are shallow brown earths, and rendzinas or grey brown podzolics. The association on which turloughs are most common, number 33, has shallow brown earths and rendzinas as the principal soils and the parent material of limestone diamicton is noted as shallow in places. Turloughs are less common in the drumlin areas where the principal soils are gleys and grey brown podzolics.

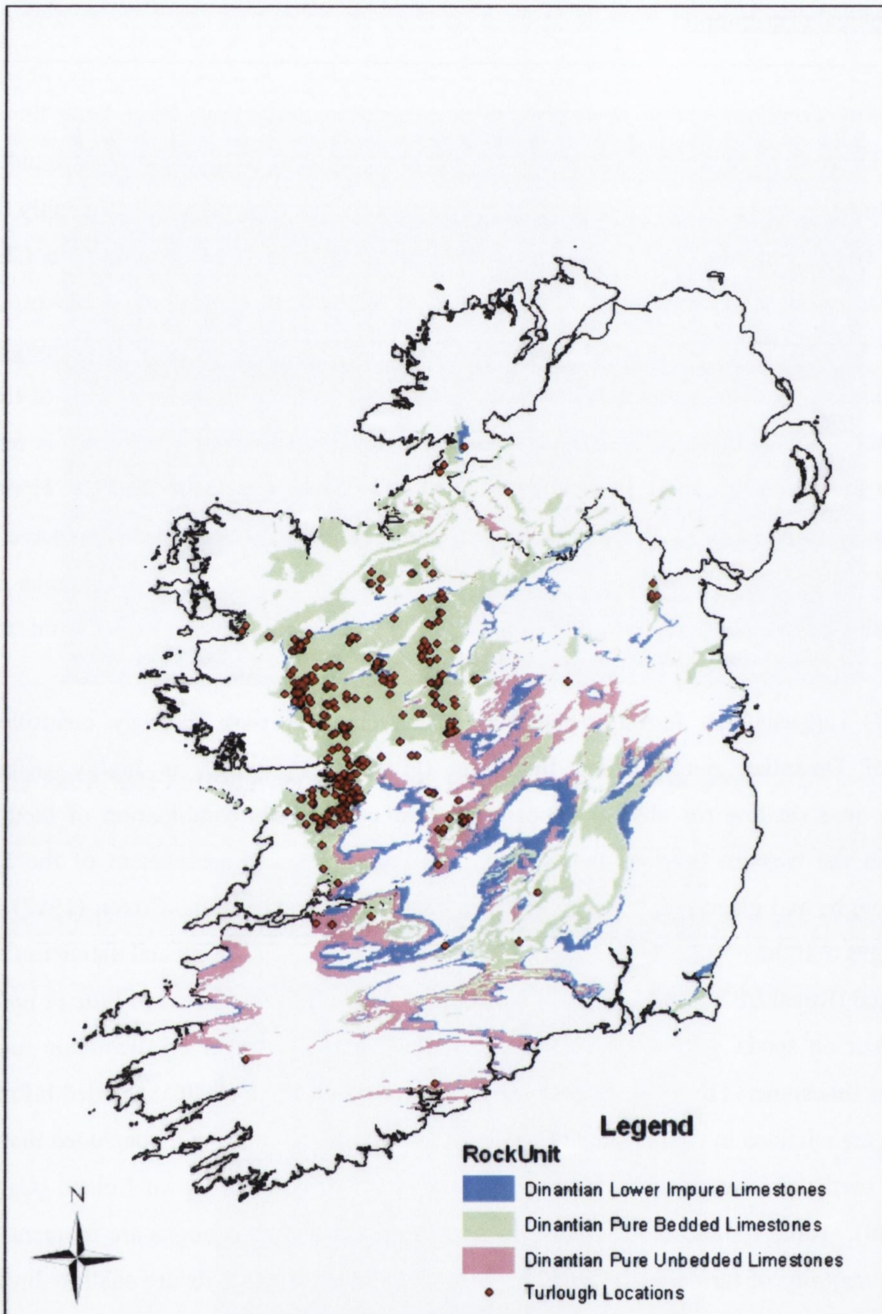

Figure 1.1: National distribution of the 308 turloughs in the Geological Survey Ireland karst database in relation to three limestone rock units (Geological Survey Ireland, GSI).

Table 1.1: **Relationship between turlough distribution and soil associations as shown on the Soil Map of Ireland (Gardiner and Radford 1980 after Coxon, 1987). (F.U.L=flat to undulating lowland; Limestone Covered % = % of limestone covered by soil association).**

Assoc. No.	**Relief Division**	**Limestone Covered %**	**Principal Soil (Associated Soil) Parent Material**	**No. of turloughs on the Association**	
				Wholly	**Partly**
33	F.U.L (dry)	8	Shallow brown earth/rendzina (grey brown podzolic, gley, peat) Limestone till, shallow in places	38	9
31	F.U.L (dry)	10	Minimal grey brown podzolic (gley, brown earth, basin peat) limestone till	13	3
7	Hill	2	Rendzina (lithosols, shallow brown earth) Limestone	7	4
32	F.U.L (dry)	8	Degraded grey brown podzolic (peat, brown earth, gley, podzol) mostly limestone till	7	2
28	Drumlin (dry)	8	Grey brown podzolic (gley, interdrumlin peat and peaty gley) mostly limestone till	3	3

1.2.3 Other similar landforms and habitats

Turloughs have been considered as peculiar to Ireland for 300 years (Nelson, 1991) but analagous habitats are found in areas associated with a similar geology, hydrology and climate (Reynolds, 1996) within the UK, Germany, Denmark, Estonia, Slovenia and Canada. Under the UK BAP (1998) turloughs and fluctuating meres are categorised as "aquifer fed naturally fluctuating water bodies". The fluctuating meres of Norfolk Breckland are glacially formed hollows with a thin covering of drift (Trist, 1979) but differ from turloughs in that they occur over chalk, have highly lagged groundwater fluctuations and sometimes have dry periods of several years. An element common to both turloughs and meres is the prevalence of aquatic and semi-aquatic mosses such as *Fontinalis antipyretica* and *Cinclodotus fontinaloides*.

The poljies or uvalas of Eastern Europe are glacially formed hollows and do occur on carboniferous limestone (Coxon, 1986), however due to climatic differences and also the presence of thick sediments on the flat floor, the flooding regimes of these landforms are generally distinct from turloughs in that many can remain empty for more than a year. .

Located in the montane limestone regions of Slovenia, Lake Cerknica is locus typicus for intermittent lakes, and is associated with Cerknisko poljie which extends over 38 square kilometers, a much greater area than any turlough. The flooding regime of this particular poljie is more regular than that of turloughs as it typically completely floods twice a year, in spring and late autumn to early winter. Throughout the poljie, vegetation of an amphibious nature is abundant during the dry phase including turlough species such as *Mentha aquatica*, *Myosotis scorpioides* and *Teucrium scordium* (Krzic and Gaberscik, 2005). It seems that Lake Cerknica is turlough-like but on a much larger scale, with a more regular flooding regime. Habitats apparently similar to turloughs are also found in eastern Canada, where depressions with seasonally fluctuating lakes occur in areas which have been subjected to prolonged karstification interrupted by glaciation (Cote *et al.,* 1990).

There are also a number of permanent lakes in Ireland with some turlough features e.g. Lough Bunny, Co. Clare and Whitelake, Co. Westmeath, with extensive marginal shallows that dry out (Byrne and Reynolds, 1982). Banyoles Lake in Catalonia, Spain is a similar, but more complex phenomenon associated with a great number of active karstic manifestations: collapse depressions, intermittent springs and karren fields, although here the dry Mediterranean summer leads to a relatively predicTable seasonal pattern of filling and emptying (Sanz, 1983; Abella, 1986a).

1.2.4 General ecology

The high conservation value of turloughs is not only attributed to their restricted geographical range but also to their diverse and rare plant species, the fact that they provide the only habitat in Britain and Ireland for the fairy shrimp (*Tanymastix stagnalis*) is found (Young, 1975; 1976). Turloughs also provide over wintering grounds for many migratory bird species, including Greenland white-fronted geese and whooper swans (de Buitlear, 1995). Six plant species that occur in turlough basins are assigned to the *Rare* category in the Irish Red Data Book (Curtis and McGough, 1988) including *Filipendula vulgaris, Frangula alnus, Limosella aquatica, Potentilla fruticosa, Rorippa islandica, Viola persicifolia.*

The development of turlough vegetation would be expected to have begun during dry periods of sufficient length to allow for the establishment of terrestrial plant communities characterised by the conditions at the site, including appropriate soil conditions for germination (Grime, 1979; Odum 1996).

Niering (1989) highlighted the fact that traditional successional concepts relating to subsequent development of plant communities have limited usefulness when applied to wetland dynamics and many wetlands, such as turloughs, are maintained at so called permanent successional stages by a regular or irregular input of energy in the form of floodwaters (Hejny and Segal, 1998). Allogenic processes, such as the hydrologic condition, profoundly influence ecological function (Neiring, 1989) by regulating biogeochemical cycling and vegetation pattern, and therefore primary productivity (Mitsch and Gosselink, 2000). Autogenic processes may also influence turlough ecosystem development as plant production of organic matter may raise the level of certain basin areas, resulting in a drier environment in which different species succeed. Mitsch and Gosselink (2000) suggest that all wetlands share the common theme that development insulates the ecosystem from its environment. At species level, this occurs through genetic adaptations to periodic inundation, such as the morphological and physiological adaptations exhibited by the turlough-form of *Ranunculus repens* (Lynn, 1998; Lynn and Waldren, 2001). At the ecosystem level, it occurs primarily through peat production which shifts the main source of nutrients to recycled material within the ecosystem (Mitsch and Gosselink, 2000). This suggests that the intrasystem mineral cycling aspect of turlough biogeochemistry is an important driver of plant productivity and highlights the importance of turlough substrates as both the medium in which chemical transformations take place and the primary storage of available nutrients for most plants.

According to Hejný and Segal (1998) the concept of wetland trophy refers to habitat typification according to hydrochemistry, however Tynan *et al.* (2005) highlight that turlough typification according to substrate trophy is also required to adequately understand turlough vegetation community dynamics during the terrestrial phase. The natural trophic status of turloughs is thought to be determined by the nature of floodwaters arriving to a basin, the soil/substrate types present and the interaction between these two factors (Goodwillie, 2001, Tynan *et al.,* 2005). Trophic status is also influenced by grazing practices, anthropogenically enriched floodwaters and occasionally the application of fertilisers (Goodwillie, 2001). Goodwillie (2001) notes that the proportion of dissolved nutrients and sediments trapped in turlough soils and substrate and the extent to which nutrients are released to the water column are poorly understood due to a lack of quantitative data generated from integrated research. The direct influence of primary productivity on shell and tissue growth of basomatophoran freshwater pulmonates has been well documented (e.g. Eisenberg, 1966) and populations from unproductive habitats have the lowest growth rates. Byrne *et al.* (1989) studied the lifecycles and shell growth rates of two species of freshwater snails in two turloughs and found the mean generation shell growth rates were the lowest yet reported for both species, reflecting the unproductive nature of the two turloughs (plate 1.4).

Generally, however, wetlands act as sinks for nutrients (Yates and Sheridan, 1983; Peterjohn and Correll 1984; Pinay and Decamps, 1988) which is demonstrated by the use of constructed wetlands for water quality improvement (e.g. Kadlec and Knight, 1996). Nutrient transformation processes such as sorption, coprecipitation, active uptake, nitrification and denitrification remove P and N from the free-flowing water of a wetland and transfer them to the substrate and biota for storage (Sloey *et al.,* 1978). The periodic drying up of a wetland such as a turlough will, however, have a marked effect on system function as the aquatic component disappears, soil microbial processes become terrestrial and aquatic vegetation is available to consumers from adjacent terrestrial areas (Howard-Williams, 1985).

Plate 1.4: Snail shells on the surface of peaty gley soil near a swallow hole in Caranavoudaun, turlough.

Although the terms eutrophic, mesotrophic and oligotrophic (Naumann, 1919) are generally accepted, great confusion exists concerning their meaning and limitations, and their application for turlough conservation. Assessment of the trophic status of turloughs is complicated by the transitional nature of the habitat and debate persists as to whether focus should be placed on monitoring the nutrient status of the aquatic and/or terrestrial component. This situation is further complicated by the fact that in a botanical context oligotrophy is used in a broader sense including both the oligotrophy and dystrophy used by limnologists (Hejný and Segal, 1998). Goodwillie (2001) states that turloughs are generally eutrophic systems, as ground and surface water sources bring sediment and dissolved nutrients into the turlough basin. He also states however that it is clear that there are eutrophic and oligotrophic turloughs as well as all gradations in between, and that there are richer patches within each basin along the shore lines of winter floods and close to the swallow holes through which the sites empty.

1.2.5 Turlough classification

The highly variable nature of turloughs is reflected by the fact that they can range from small, compact basins <10 ha to sprawling complexes of approximately 280 ha. Turloughs also vary with regard to depth, topography, groundwater connections and inundation patterns. Stimulated by the considerable challenges this natural variation poses for habitat management, efforts have been made to group turloughs according to their hydrological patterns and physical features and to relate these to the ecology of the basins. Recent developments under the Water Framework Directive have attempted to characterise the karstic groundwater bodies associated with turloughs and evaluate their influence on trophic status (Tynan *et al.,* 2005). This provides a progression in terms of turlough conservation assessment from an individual turlough approach to a more holistic classification system. Previous classifications which take into account more than one aspect of the turlough systems have been developed by Coxon (1986) and Goodwillie (1992). Coxon (1986) takes into account a number of turlough characteristics and groups turloughs on the basis of combined morphology, deposits, vegetation and duration of flooding using multivariate statistics. Work on terrestrial beetles by Regan (2003) resulted in statistical groupings with potential links to site nutrient status and duration and speed of filling and emptying. In most cases, all of these authors were hampered by a lack of quantitative data on one or more characteristics of the turlough.

According to recent turlough classification studies conducted by Tynan *et al.* (2005) on turlough flow systems, turloughs can be divided into five broad groups (Table 2.1) and the majority of turloughs are associated with Conduit (Type 1.), Shallow epikarst (Type 2.) and Combined flowsystems (Type 3.). A minority of turloughs have substantial riverine input (Type 4.) and receive distributed flow from different sediment types (Type 5.). Conduit/conduit type flow systems comprise of deep conduit, conduit/fracture and/or deep epikarst conduit flow. These are high storage systems which can support large volumes of flow, where recharge to the flow system may occur at some distance. The authors attribute the relatively high trophic status of turloughs within this type of system to the high cumulative mass loading of nutrients and sediments to the basins as a result of the large volumes and high velocity of groundwater from large catchment areas. In shallow epikarst flow system groundwater flows in the upper 2-5m of karst (epikarst) characterised by clints, grikes and solution opened joints and fissures. These are low storage systems which support low volumes of flow where recharge is probably within the local topographic catchment.

The authors conclude that the low trophic status of turloughs occurring in this type of basin is attributed to the low nutrient accumulation potential of the associated smaller catchment area relative to the conduit/conduit type flow systems, resulting in a low cumulative mass loading of nutrients to the basins.

The final type is a *combined shallow epikarst, conduit/conduit type flow system* where shallow epikarst flow frequently occurs in lateral and vertical continuity with conduit/conduit type flow systems. Depending on the proportion of the different flow system present, the response will be closer to that of either of the two systems. An indicative turlough typology has been developed by these authors based on the understanding developed of the karstic flow systems within which turloughs occur and their relationship with trophic status. This indicative typology comprises five main types of 'natural' turlough/turlough environments, that is those which have not undergone anthropogenic impacts. Two of these types (Types 1 and 2) contain the majority of turloughs studied, and based on the relatively large sample of turloughs studied this proportion is probably true for the turlough population.

Table 1.2: Classification of turloughs according to karstic flow system (Tynan *et al.,* 2005).

Non-anthropogenically impacted turlough types
Type 1: Conduit/conduit type flow system turloughs, with relatively high trophic status.
Type 2: Shallow epikarst type flow system turloughs, with low trophic status
Type 3: Combined conduit/conduit type, shallow epikarst type flow system turloughs, with relatively high trophic status.
Type 4: Turloughs with riverine input with relatively high trophic status
Type 5: Turloughs receiving distributed flow from different types of sediment.
Anthropogenically impacted turlough types
Type 6: Turloughs with anthropogenic inputs

Visser *et al.* (2006) challenge the use of turlough typologies and promote an alternative dry-wet continuum concept. Exploration of presently available data for the main variables affecting turlough ecology by these authors suggests that turloughs do not split into distinct types and that there is one continuum from dry to wet sites, which affects all aspects of turlough ecology. These authors also highlight the pitfalls of trying to fit turloughs within typologies that are weakly supported by the data on which they are based and emphasise the scope that the dry-wet continuum provides for a more flexible approach to turlough conservation. Further research on relationships between hydrological signatures of turloughs and biological communities is required to test current turlough typology and dry-continuum hypotheses.

1.3 Turlough soils

1.3.1 Turlough soil types

As a consequence of geomorphological and hydrological variations among turloughs, turlough soils are complex and highly variable in their origin and distribution (MacGowran, 1985; Coxon, 1986) and a wide range of soil types occur in turloughs in comparison to other wetlands. Soil types are taken here to include all turlough substrates including marl deposits and peats. Jenny (1941) proposed that soil characteristics are a function of the complex interaction among at least four variables including parent material, organisms, climate, topography and the time that these variables have had to interact. The soil survey of Ireland, conducted by an Foras Taluntais, does not deal specifically with types of habitat or landform, and the scale of the mapping is such as to generally make no distinction between a turlough and the surrounding land except in the case of vary large turloughs (MacGowran, 1985). Coxon (1986) and MacGowran (1985) provide information on the types of deposits found within turloughs which would be expected to influence the development of soils. Studies of the pedology of 16 turloughs in Galway, Clare and Mayo by MacGowran (1985) noted that wherever the sediments in the bottom of a turlough have been examined they often feature peat or sand/silt/clay mixtures underlain by marl which is generally thought to have been deposited in turloughs during the Pleistocene (Sweeting, 1953; Watts, 1963; Drew, 1976; Crabtree 1982). Coxon (1986) investigated the deposit/sediment types present within the main basin areas of 90 turloughs to one metre depth and classified them into six groups based on their colour, organic matter content, calcium carbonate content and non-calcareous inorganic content. These six groups were the peat, marl, peat-marl, silt/clay, sand/silt and diamicton and a given turlough can contain several of these categories. The majority of turloughs (69 out of 90) contain at least one of the deposits peat, marl or peat-marl.

She used this information to classify turloughs based on their deposit types, turloughs containing marl, turloughs containing peat or peat-marl but not marl, turloughs containing silt/clay only, turloughs containing sand/silt or sand/silt plus silt/clay and turloughs containing diamicton (or diamicton plus silt/clay). The suggestion that many turloughs were permanent lakes and that their period of transition to seasonal lakes is unknown would be expected to have implications for soil development. Soil development within individual turloughs may also depend on the drainage characteristics of the underlying bedrock (Coxon, 1986) and would be expected to be heavily influenced by repeated flooding and drainage resulting in hydric soils, defined as "soils that formed under conditions of saturation, flooding or ponding long enough during the growing season to develop anaerobic conditions in the upper part" (Mitsch and Gosselink, 2000).

Wetland soils are either mineral soil types or organic soil types (where a soil with less than 20 percent organic matter on a dry weight basis is a mineral soil) (Mitsch and Gosselink, 2000) and turloughs have numerous variants of each (MacGowran, 1985; Coxon, 1986). MacGowran (1985), building on previous work by Praeger (1932) and Sweeting (1953), provides a comprehensive inventory of the soil types present within 16 turloughs located within the Gort Lowlands, Burren Hills and Burren Lowlands. He concluded that turlough soils are generally poorly developed, shallow soils with simple profiles which can be classified according to the Irish Soil Survey as organic rendzinas and rendzina-like soils (loamy and sandy), which generally occur at the upper parts of these basins exceptionally exposed to flooding, grading to gleys (peaty and sandy), river silts and raw marl and peats. MacGowran (1985) states that at the highest level in turloughs several variants of rendzinas (shallow soils on limestone parent materials) occur, which are characteristic of Irish karst, where the major elements of variation include the organic matter content, the texture and degree of gleying. Drainage is free to excessive and where the soil is low in organic matter it can become dry in hot weather, prone to dessication. Gleys were identified as being the most common soil type where drainage is normally impeded, but wherever the parent material is marly, and especially where the uppermost horizon is very thin, this soil type is also prone to dessication. Below the level of the gleys there is either permanent marsh or a shallow lake/river with or without marl deposits. Coxon (1986) also identified the deposits immediately below the surface using the same criteria she used to classify the deposits at one metre depth and classified them into five groups which can be related to both duration and depth of inundation including Marl (or marl plus peat-marl cf Section 2.2.5), Peat (or peat plus peat-marl), Silt/clay, Sand/silt or diamicton (poorly sorted deposits) and Variable (mixture of deposits: peat or marl, peat-marl in parts, diamicton in parts).

Goodwillie (2001) notes that the range of turlough soil types is broad in comparison to other wetlands and qualitative evidence suggests that these soil types encourage the establishment of different vegetation types having different requirements and tolerances for nutrient availability, draining properties and presence of toxic substances (Goodwillie, 1992).

1.3.2 Factors affecting turlough soil nutrient heterogeneity

Robertson and Gross (1994) state that it is nearly an ecological truism that below ground resources in plant communities are heterogeneously distributed in both space and time. Such heterogeneity in wetlands such as turloughs is the result of differences in parent material, elevation, topography, erosional or depositional environment, frequency of flooding, vegetation, pedogenic effects, and hydrology (Johnston *et al.,* 1984; Hayati and Proctor, 1990; Gaston *et al.,* 1990; Farrish, 1991; Reese and Moorhead, 1996).

However whilst this heterogeneity in nutrient availability is well recognised, the scale or extent to which this spatial or temporal variation occurs in turloughs during the terrestrial phase, and how this might influence plant community structure and sampling strategies for conservation assessment are poorly understood. The majority of soil spatial research is focussed on refining agricultural management practices for maximum yield potential (e.g. Blackmore, 1994; Chancellor and Goronea, 1994), and for assessing the effects of agriculture on environmental quality such as the transport of phosphate to surface-water (e.g. Daly *et al.,* 2001; Daniel *et al.,* 1998; Van der Zee and Van Riemsdijk, 1988). Ecological, and in particular wetland, soil spatial studies are more limited in number and are primarily concerned with characterising variation in soil properties for adequate site assessment with the aim of examining differences in soil properties among sites and evaluating environmental and ecological functions of the areas of interest (Brinson *et al.*, 1981; Wharton *et al.*, 1982; Johnston *et al.*, 1984; Gaston *et al.*, 1990; Hayati and Proctor, 1990; Vitt and Chee, 1990; Farrish, 1991; Bridgham and Richardson, 1993; Reese and Moorhead, 1996; Stolt *et al.*, 2001).

The environmental variables that promote variability in turlough soil physical characteristics would be expected to promote patchiness in nutrient availability. For example, parent materials influence the physical properties of soil, such as soil texture and the volume of soil available for exploitation, and limestone parent materials often lead to shallow or rocky soils resulting in a smaller volume of soil (<2 mm material) capable of supplying nutrients, and to increases in the patchiness in nutrient supply by segregating the pockets of soil (Stark, 1994).

Nutrient availability also tends to vary with soil depth and is generally higher in surface layers because of the favourable pH, the accumulation of organic matter and the greater ease of root penetration.

These layers also experience greater fluctuations in moisture and temperature cycles and these wetting and drying cycles promote release of nutrients by increasing turnover of microbial biomass and physically protected (locked within mineral aggregates) organic matter (Birch, 1960; Witkamp, 1969).

Nutrient cycling in soils is inherently spatio-temporally variable as the rates of nutrient production and consumption are driven by variable soil ecological (Bascompte and Solé, 1998; Kareiva and Tilman, 1997) and physical factors. Soil P is in a constantly changing equilibrium with rapid fluxes of P between different pools, controlled by biological and physical processes. Biological processes include, amongst others, enzyme and microbial mediated decomposition, dissolution/diffusion of animal excreted P, immobilisation by microbial and enzyme and microbially mediated mineralization and plant uptake.

The physico-chemical transformations and fractions involved in soil P cycling include desorption from metal surfaces, dissolution from Ca phosphates (pH dependent) leaching and surface runoff losses (small), occlusion of sorbed P into aggregate structure (slow), migration of occluded P to aggregate (de) sorption surfaces (slow), sorption and precipitation of P to aggregate surfaces (Styles, 2004). The availability of P is therefore a function of both soil biology and chemistry, whereas N availability depends more on soil biology. Plants absorb most of their nitrogen in the ammonium (NH_4^+) and nitrate (NO_3^-) forms of nitrogen (Marschner, 1986). The abundance of inorganic N concentrations and the predominant form in the soil are determined by mineralization of organically bound nitrogen and nitrification rates which are influenced by the nature and content of organic matter, redox potential, pH and temperature, and microbial conversions (Ponamperuma, 1972).

The unique and diverse hydrologic conditions in turloughs are thought to markedly influence biogeochemical processes. Soil moisture, organic matter and marl deposition are potentially three of the most important factors promoting heterogeneity in plant nutrient availability. Fluctuating waterTables can lead to substantial temporal and spatial heterogeneity in nutrients, especially when solubilities are strongly affected by redox potential, for example iron and manganese which may increase in availability to the point that toxicities develop (Stark, 1994). Within the turlough environment soil moisture would be expected to exert a profound influence on microbial activity and spatial patterns of decomposition, nutrient supply and root herbivory (Ettema and Wardle, 2002).

In addition, heterogeneity in most well-developed soils results from the amount, location, timing and chemical composition of organic inputs, and from the effect of soil microorganisms on decomposition, immobilisation and mineralization of soil nutrients from soil organic components (Stark, 1994). Heterogeneity in organic matter distribution caused by differences in vegetation types is fairly large scale and individual plants will experience this variation at sharp vegetation boundaries.
The greatest influence that microorganisms have on nutrient heterogeneity is through their role in nutrient release and immobilisation during litter decomposition (Stark, 1994).

The chemical composition of the litter (e.g. C:N ratio) and environmental factors such as temperature and moisture control the rate of microbial activity and whether nutrients will be immobilised in microbial tissue or become available for plant uptake (Park, 1976; Paul and Clark, 1989). Finally, marl deposition varies with turlough typologies as it is driven by the alkalinity of floodwaters. The patchy deposition of marl within turlough basins due to irreglular topography and depth of flooding (Coxon, 1994) adds complexity to the nutrient cycling processes in turlough soils, as its high alkalinity and lack of aeration create specialised conditions for plant roots (Goodwillie, 2001).

Table 1.3: Main vegetation communities in turlough basins from the edge down to the basin floor (Goodwillie, 1992). Species names and taxanomic order follow Webb *et al.* (1996). The letters refer to trophic status A (eutrophic), B (mesotrophic), C (oligotrophic, calcareous) and D (oligotrophic, peaty) and the numbers (2-12) to increasing depth. Habitat Wetness Groups: G = Grass dominated, S = Sedge dominated, W = Woodland and A = Aquatic. Flooding Duration = associated annual duration of flooding. N/A = Not Available.

Plant Community	Indicator species	Habitat Wetness Groups	Flooding Duration
2A. *Lolium* grassland	*Lolium perenne, Poa trivialis, Bellis perennis, Leontodon autumnalis, Cirsium arvense*	G	Group 1 (0-56%)
2B. Poor grassland	*Carex hirta, Phleum pratense, Festuca arundinacea, Deschampsia caespitosa, Prunella vulgaris, Ranunculus acris, Elymus repens*	G	Group 1 (0-40%)
2C. Limestone grassland	*Festuca rubra, Achillea millefollium, Galium verum, Prunella vulgaris, Filipendula vulgaris*	G	N/A
2D. Peat grassand	*Molinia caerulea, Potentilla erecta, Succisa pratensis, Juncus effusus, Juncus conglomerates, Cirsium dissectum*	G	N/A
3A. Tall herb	*Phalaris arundinacea, Filipendula ulmaria, Festuca arundinacea, Vicia cracca, Lysimachia vulgaris, Thalictrum flavum, Iris pseudacorus*	G	Group 3 (23-100%)
3B. Sedge heath	*Deschampsia caespitosa, Molinia caerulea, Carex panicea, Carex hostiana, Danthonia decumbens, Nardus stricta, Plantago maritima, Festuca arundincea*	G	N/A
3C. Flooded pavement	*Molinea caerulea, Carex hostiana, Rhiananthus minor, Carex flacca, Centaurea nigra, Briza media*	G	N/A
3W. *Rhamnus* wood	*Crataegus monogyna, Rhamnus catharticus, Prunus spinosa, Fraxinus excelsior, Viburnum opulus, Euonymous europaeus*	W	N/A
4B. *Potentilla reptans* (spp. rich)	*Filipendula ulmaria, Carex flacca, Carex panicea, Lotus corniculatus, Galium boreale, Salix repens, Potentilla reptans, Viola canina*	S	Group 3 (17-100%)
4D. *Schoenus* fen	*Schoenus nigricans, Molinia caerulea, Achillea ptarmica, Cirsium dissectum, Parnassia palustris*	S	N/A
4W. *Frangula alnus/ Potentialla fruticosa*	*Frangula alnus, Potentilla fruticosa, Rhamnus catharticus, Rubus caesius*	W	N/A
5A. Dry weed	*Rumex obtusifolius, Rumex crispus, Potentilla anserina, P. reptans, Carex hirta, Polygonum aviculare, P. amphibium, Rorripa palustris*	S	N/A
5B. *Potentilla reptans* (spp. poor)	*Potentilla reptans, Carex nigra, Carex flacca, Trifolium repens, Lotus corniculatus, Rumex crispus, Filipendula ulmaria, Viola persicifolia*	S	N/A
5D. Sedge fen	*Carex hostiana, Carex panicea, Succisa pratensis, Potentilla erecta, Molinia caerulea, Briza media, Schoenus nigricans*	S	Group 1 (0-68%)
5E. *Carex flava*	*Carex flava, Carex panicea, Carex nigra, Hydrocotyle vulgaris*	S	N/A
6A. Dry *Carex nigra*	*Carex nigra, Agrostis stolonifera, Potentilla anserina, Plantago lanceolata, Rumex crispus, Phalaris arundinacea*	S	Group 1 (0.4-83%)

Table 1.3 contd: Main vegetation communities in turlough basins from the edge down to the basin floor (Goodwillie, 1992). Species names and taxanomic order follow Webb (1996). The letters refer to trophic status A (eutrophic), B (mesotrophic), C (oligotrophic, calcareous) and D (oligotrophic, peaty) and the numbers (2-12) to increasing depth. G = Grass dominated, S = Sedge dominated, W = Woodland and A = Aquatic. Flooding Duration = associated annual duration of flooding measured using pressure transducer based instruments known as Divers (Tynan *et al.*, 2005).

Plant Community	Indicator species	Wetness Group	Flooding Duration
6B. Wet *Carex nigra*	*Carex nigra, Senicio aquaticus, Caltha palustris, Eleocharis palustris, Hydrocotyle vulgaris, Myosotis scorpiodes, Juncus articulatus, Phalaris arundinacea*	S	Group 3 (0-100%)
6D. Peaty *Carex nigra*	*Carex nigra, Potentilla palustris, Menyanthes trifoliata, Juncus articulatus*	S	N/A
7A. *Polygonum amphibium* (grassy)	*Agrostis stolonifera, Potentilla anserina, Polygonum amphibium, Ranunculus repens, Galium palustre, Leontodon autumnalis*	S	Group 3 (0-100%)
7B. Tall sedge	*Carex elata, Carex acuta, Carex rostrata, Carex vesicaria*	S	N/A
8A. *Polygonum amphibium*	*Polygonum amphibium, Agrostis stolonifera, Myosotis scorpiodes, Eleocharis palustris*	A	Group 2 (17-76%)
8B. Wet annuals	*Polygonum persicaria, Rorippa islandica, R. amphibia, Eleocharis palustris, Agrostis stolonifera, Galium palustre*	A	N/A
8C. *Cladium* fen	*Cladium mariscus, Carex lasiocarpa, C. viridula*	A	N/A
9A. Temporary pond	*Glyceria fluitans, Agrostis stolonifera, Ranunculus trichophyllus, Myosotis scorpiodes, Rorippa amphibia, Apium inundatum, Eleocharis palustris, Polygonum hydropiper, P. minus*	A	Group 2 (17-96%)
9B. *Eleocharis acicularis*	*Eleocharis acicularis, Lythrum portula, Limosella aquatica*	A	N/A
9C. Marl pond	*Juncus articulatus, J. bulbosus, Baldellia ranunculoides, Eleocharis multicaulis, Litorella uniflora, Potamogeton coloratus, P. gramineus, Carex lepidocarpa, Eleogitan fluitans*	A	Group 2 (9-72%)
10A. *Oenanthe aquatica*	*Oenathe aquatica, Sparganium emersum, Rorripa amphibia*	A	
10B. Ditch	*Berula erecta, Nastutium officinale, Apium nodiflorum*	A	
11A. Reed bed	*Phragmites australis, Schoenoplectus lacustris, Sparganium erectum, Ranunculus lingua, Juncus subnodulosus*	A	Group 2 (17-98%)
11B. Peaty pond	*Equisetum fluviatale, Sparganium erectum, Alisma plantago-aquatica, Menyanthes trifoliata, Hippuris vulgaris, Lemna spp., Carex rostrata*	A	
12 Open water (fluctuating)	*Potamogeton natans, P. crispus, P. berchtoldii, Myriophyllum spicatum, Nuphar lutea*	A	Group 2 (26-63%)

1.3.3 Turlough plant-soil relationships

A comprehensive turlough vegetation survey encompassing 61 turloughs was conducted by Goodwillie (1992) through which 32 distinct vegetation units were identified. Identification of communities was based on the presence of indicator species which grow under a narrow range of habitat conditions and physiognomical characters. The 32 communities were divided into a series of one to twelve divisions generally occurring in the same relative positions with increasing depth in the turlough basin, each division was further split into trophic types (Table 1.3). Goodwillie states that the depth divisions correspond broadly to depth of submergence and that coverage by water is the main controlling factor in vegetation and has the largest part to play in its zonation. Hydro-ecological studies conducted by Tynan *et al.* (2005) found relationships between the distribution of some of these vegetation units, within a limited number of turloughs, and flood duration (Table 1.3). Vegetation communities in Group 1 appear to be constrained in their distribution by a maximum flooding duration value, Group 2 communities were found to be constrained in their distribution by a minimum flooding duration value and Group 3 was identified as consisting of communities which occur across a very wide range of flood duration conditions with no obvious relationship between Goodwillie's depth divisions. A complementary turlough vegetation dominance scheme based on Goodwillie's mapping was devised by Eugenie Regan and James Moran, NUI Galway (Tynan *et al.,* 2005.). Goodwillie's communities (excluding woodland communities) are amalgamated into three vegetation types, comprising grassland, sedge and aquatic community types. These types are generally associated with increasing habitat wetness. This approach is consistent with the generally observed relationship between various wetland species and wetness (Euliss, *et al.* 2004; Wierda, *et al.* 1997 as cited in Tynan *et al.* 2005)

Current interest in the nature of the relationship between variability in plant nutrient availability and plant species diversity in wetlands is driven by widespread observations of declines in species richness associated with nutrient enrichment (Morris, 1999; Vitousek, 1994). Experimental studies within turloughs showed a reduction in species diversity and an increase in biomass as a result of fertiliser application in two turloughs: Coole turlough, Co. Galway (mesotrophic) and Gortlecka turlough, Co. Clare (oligotrophic) located in the West of Ireland (Kimberley, 2002). Species diversity was thought to have declined because certain species such as *Potentilla anserina* and *Rumex acetosa* have the capacity to rapidly assimilate excess nutrients and competitively exclude species lacking this capability, suggesting that soil fertility plays a critical role in turlough vegetation ecology in addition to hydrological regime. The extent to which environmental factors determine spatial variation in vegetation community structure is however in large part related to scale (Moles *et al.,* 2003).

Soil pH, organic matter content, and assorted mineral element concentrations have been shown to vary within some plant communities by an order of magnitude at spatial scales of 5 m or less (e.g. Raupach, 1951; Trangmar *et al.,* 1987) and in a number of cases this variation appeared to be associated with changes in plant species distributions (e.g. Snaydon, 1962; Turkington and Harper, 1979; Inouye *et al.,* 1987). At the local or within-turlough scale, the most striking aspect of turlough vegetation is not the abundance of rare species but rather the fact that whilst many turlough species are common, the local populations can show peculiar characteristics, where ruderal species associated with dry habitats persist in deep zones at the turlough base and where wetland species occur in close proximity to calcareous, species rich grassland (Praeger, 1932; MacGowran, 1985; Coxon, 1986; Goodwillie, 1992). Such unusual species distributions are thought to be determined by both abiotic and biotic factors (Grime, 1979; Austin, 1990). Generally, depth, duration and timing of flooding are the main abiotic environmental variables determining zonation in vegetation along the flooding gradients of wetlands (Blom and Voesenek, 1996). Individual plant species may be affected directly due to their germination requirements with regard to soil moisture (Keddy and Ellis, 1985; Coops and Van der Velde, 1995) or different tolerances to flooding as seedlings and adults (e.g. Blom *et al.,* 1994; Clevering *et al.,* 1995). Biotic interactions determining the zonation of species along flooding gradients include competition (Austin, 1990) and nutrient availability (Bedford *et al.,* 1999) and nutrient limitation (Chapin *et al.* 1986). Understanding the patterns and causes of spatial variability in the vegetation community structure of turloughs can contribute to the resolution of important questions about turloughs such as whether small to medium scale edaphic heterogeneity is characteristic of these wetlands and whether this could be a factor in the maintenance of botanical species richness. To evaluate potential relationships between patterns of soil nutrient cycling and turlough plant community structure first requires the demonstration that nutrient availability can vary significantly within and among turloughs.

1.4 Assessment and monitoring of turlough conservation status

Drainage and eutrophication, the latter of which is principally linked to agricultural intensification in the form of fertiliser application, over-grazing and/or anthropogenically enriched floodwaters, constitute the main threats to the quality of the turlough habitat (Goodwillie, 2001) (plate 1.5 and 1.6). The restricted global distribution of turloughs and the presence of characteristic fauna and vegetation, including some locally rare species, has lead to their designation as a priority habitat (Code 3180) (a natural habitat type that is in danger of disappearance) under Annex 1 of the 1992 EU Habitats Directive (92/43/EEC) to which Ireland is committed.

The importance of turloughs in a European context is emphasized by Goodwillie (2001) where he notes that the turlough is one of only two priority wetlands, the second being mediterranean temporary ponds. This Directive commits the State to various actions, including conservation of the habitat, monitoring of the conservation status and adequate management to ensure favourable conservation status.

Accordingly, the State has nominated many turloughs as candidate Special Areas of Conservation (SAC), either individually or in conjunction with other habitats as an SAC complex. Some turloughs are also listed as Special Protection Areas (SPA) under the provisions of the EU Birds Directive (79/409/EEC). Together, SACs and SPAs form part of the Natura 2000 network of protected areas across the EU. The European Water Framework Directive (WFD) (2000/60/EC) is the first piece of European water legislation that encompasses all waters: groundwaters, rivers, lakes, estuarine and coastal waters. Whilst turloughs are important for both their aquatic and terrestrial ecologies, they were classified as Groundwater Dependent Terrestrial Ecosystems (GWDTE) for the purpose of the Water Framework Directive because their aquatic phase is not permanent. The WFD requires good water status for all European waters by 2015, to be achieved through a system of participatory river basin management planning and supported by several assessments and extensive monitoring (Mostert, 2003). The WFD objective for wetlands identified as a GWDTE is to achieve good groundwater status, including the prevention of impact on associated surface waters (Annex V (2.1.2 and 2.3.2).

Turlough conservation status is currently assessed by National Parks and Wildlife Service (NPWS) using a measure of the trophic sensitivity of individual turloughs based on assigning Ellenberg Fertility Scores to vegetation communities. This approach uses the occurrence of certain indicator plant species, associated with vegetation communities mapped by Goodwillie (1992), to provide an indication of the degree of N enrichment within the site (Hill *et al.*, 1999). The turloughs are then categorised and ranked according to the proportional area of communities with low Ellenberg Scores (<4), i.e. the proportional area of low productivity, nutrient-sensitive plant communities. These trophic sensitivities must be considered with caution however as the vegetation maps, upon which they are based, were generated from a qualitative survey of turlough vegetation conducted over one summer season in 1990.

It is accepted by turlough ecologists that a relationship exists between the water quality, the flooding regime, the geomorphology and the substrate of a turlough, and the composition and distribution of its plant and animal communities (Working Group on Groundwater, 2004) but the degree of influence that substrate exerts on turlough ecology is one of the most poorly understood aspects of this relationship.

In order to understand turlough ecology in a holistic sense, a solid understanding of the influence exerted by soils and substrates is required but suiTable approaches for soil sampling strategies are lacking. Grigal *et al.,* (1991) note that understanding spatial and temporal variability in soil properties and relationships among soil properties presents a major challenge to ecologists attempting to assess either the present status or changes in ecosystems, as soil variability can affect both the precision of estimates and the ability to detect true underlying relationships (Mader, 1963; Blyth and MacLeod, 1978).

Plate 1.5: Internal drainage ditch within Lough Cuil Reasc turlough, Co. Clare during Summer 2004.

Plate 1.6: Closely cropped sward and high levels of dung deposition indicate a high level of grazing in Garryland turlough, Co. Galway.

1.5 Overall aims and thesis structure

The overriding aim of this project is to contribute to a better understanding of turlough soil nutrient dynamics and trophic conditions, and their associations with vegetation types and current turlough trophic assessments. Focus is placed on investigating spatial and temporal soil property variability and the associated implications for turlough soil nutrient assessments. This is conducted by assessing the links between spatio-temporal variability of soil nutrient status, soil type and vegetation community structure at both catchment and within-turlough scales. At the catchment scale, focus is placed on determining whether turloughs located within specific types of karst flow systems have common soil nutrient properties and spatial trends. At the within-turlough scale, the implications of spatio-temporal variability in nutrient status for accurate soil nutrient assessment of individual turloughs are addressed. Sampling strategy and analytical recommendations for soil nutrient assessments are key outputs. This thesis is divided into five chapters, including three relatively self-contained results chapters, according to the following divisions:

Chapter 1 provides a general introduction to the complex factors influencing turlough ecology and highlights the potential implications of spatial and temporal variations in soil nutrient status for nutrient assessment and interpreting turlough vegetation ecology.

Chapter 2 aims to identify soil nutrient-related properties characteristic of turloughs located within two catchments with contrasting nutrient loadings associated with different types of karst flow systems and investigates the implications of within-site spatial variations for making soil property comparisons among turloughs. This chapter also compares the nutrient status of common turlough soil types and investigates the relation between vegetation communities and soil nutrient properties.

Chapter 3 considers how nutrient status varies with soil type along the flooding gradient of selected turloughs occurring within similar flow systems and among turloughs occurring within contrasting flow systems. This chapter also addresses the relationships between soil nutrient properties and plant-nutrient availability.

Chapter 4 compares the temporal variations in nutrient availability among common turlough soil types and considers the implications of temporal variations for making soil nutrient assessments of individual turloughs.

Chapter 5 is a summary chapter, drawing together the overall conclusions from each of the preceding results chapters. This chapter also provides sampling and analytical recommendations for turlough soil nutrient assessments and suggestions for the focus of future turlough soil nutrient research.

CHAPTER 2. SPATIAL VARIATIONS IN SOIL NUTRIENT PROPERTIES AMONG TURLOUGHS LOCATED WITHIN TWO CONTRASTING CATCHMENT AREAS

2.1. Introduction

It is well recognised that catchments are appropriate spatial units for managing the quality of surface waters, groundwaters, and their associated wetlands, and the main unit of management of the Water Framwework Directive (WFD) (2000/60/EC) is the river basin district. By agreement between the hydrological agencies in the Republic of Ireland and Northern Ireland, the island of Ireland is divided into 40 hydrometric areas (McGarrigle *et al.*, 2002). Each area comprises a single large river catchment or a group of smaller catchments and these areas were grouped to form eight river basin districts on the island of Ireland under the provisions of the WFD (DEHLG and DOENI, 2003). The directive institutionalises ecosystem-based objectives and planning processes at the level of the river basin as the basis for water resource management (Kallis and Butler, 2001).

Karst groundwater environments, where turloughs typically occur, have been identified as particularly vulnerable to pollution (Drew, 1996), and can result in pollutants such as phosphorus being rapidly transmitted from groundwater to surface water ecosystems via springs (Kilroy and Coxon, 2005). Kilroy *et al.* (2005) examined groundwater and wetlands in the Shannon river basin in the context of implementation of the WFD. The particular wetland example of turloughs was examined in the context of the delineation of their catchment areas for risk assessment as required by Articles 3 and 5, respectively of WFD. Kilroy *et al.* (2005) state that groundwater dependent terrestrial ecosystems such as turloughs are particularly challenging in terms of delineating their catchment areas for the purposes of risk assessment and implementation of WFD measures. Article 5 of WFD required the identification of groundwater bodies at risk of failing to meet the environmental objectives set out in Article 4 and turloughs at siginificant risk were identified as those occurring within groundwater bodies at significant risk. A key challenge in the risk assessment process is to delineate catchment areas of groundwater dependent ecosystems so that assessments of diffuse, point and abstraction pressures can be carried out. Even where very detailed hydrogeological investigations involving water tracing experiments have been carried out (e.g. Drew, 2003), it is difficult to delineate firm catchment boundaries for turloughs because of the combination of localised diffuse recharge from the epikarst and point recharge from sinking streams, and because the contributing area varies over time. In the absence of detailed hydrogeological investigations, a combination of individual river waterbody catchments and groundwater body boundaries were used to define approximate turlough catchment areas.

Delineated catchment areas provide an area upon which to apply the diffuse and point pressures from phosphate, the key limiting nutrient in most freshwater systems, and abstraction pressures risk assessments by combining information on the magnitude of such pressures, pathway susceptibility and receptor sensitivity in a geographical information system (GIS) (Daly, 2004) . The concept of pathway susceptibility (i.e. the likelihood of pollutants being transmitted to a turlough) is a factor of aquifer type, soils/subsoil type and vulnerability. Catchment pedology is at the core of this risk assessment process and in general, pollutants will be transferred more easily in well drained soils, where subsoils have high permeability. Vulnerability depends on the depth of overburden above the bedrock, with extremely vulnerable areas having less than 3 m of soil and subsoil material. Conacher (2002) reiterates that geomorphology and pedology are of fundamental importance in catchment management. As water moves through catchments it carries sediments which are mobilised from one location and redeposited elsewhere and this translocation affects soil morphological, physical, chemical and biological properties. Human land-use activities are themselves influenced by the pedo-geomorphology within the catchment area (Conacher, 2002). Current turlough classification methods (outlined in Section 1.2.5) recognise the potential influence that catchment factors such as pedology, geomorphology (particularly the nature of the karst aquifer) and land-use have on the ecology of individual turloughs located within various catchment areas. A catchment based approach to turlough management (including risk assessment) and to understanding the factors driving turlough ecology is therefore the future for turlough conservation and such an approach must take into account pedological processes within turloughs in addition to those within the catchment area. Kilroy *et al.* (2005) stress that monitoring data are required to validate current turlough risk assessments and soil descriptions and nutrient assessments should form part of any future turlough conservation assessment monitoring programme.

The inclusion of soil nutrient assessments in turlough ecological studies and monitoring strategies requires an improved understanding of the relationships between turlough soils and catchment factors, such as nutrient loading, in order to determine the extent to which soil nutrient status reflects such factors. Conclusions drawn from investigations of soil variability (review by Beckett and Webster, 1971) are generally consistent in showing that variance of properties increases with size of area sampled; that some properties are more variable than others and the data rarely conform to normal distributions. Consideration of the potential implications of soil nutrient variation for making comparisons among turloughs, for detecting ecological relationships and for identifying soil related factors which influence the spatial patterns of nutrients within and among turlough catchments is therefore of fundamental importance.

Many pedological studies and ecological studies employ the type profile approach, in which one or more characteristic profiles are sampled and the subsequent analyses are taken to be representative of an homogenous soil area (Ball and Williams, 1968). It has been appreciated however that chemical variability within a soil type can be large (Smith *et al.*, 1952), emphasising the need for enhanced understanding of how nutient status varies with turlough soil types.

The major aims of this spatial aspect of this study were to

i) compare nutrient-related soil properties between two contrasting turlough catchments (karst system types), taking into account both landscape scale variation i.e. among turlough catchments and among turloughs within the same catchment, and local-scale within-turlough variation along the flooding gradients.

ii) investigate the implications of spatial variation within turloughs for making soil nutrient comparisons among turloughs occurring within the same catchment.

iii) identify soil types characteristic of each catchment and examine the variation in nutrient status within and among such soil types.

iv) investigate the relationships between vegetation types and nutrient-related soil properties associated with two different turlough catchments.

2.2. Methods

2.2.1. Turlough catchment selection

Two catchments were selected for study, including a mesotrophic/eutrophic Mixed Flow System Catchment corresponding with the Coole-Garryland SAC Complex, Co. Galway and an oligotrophic Epikarst Flow Catchment corresponding with the East Burren SAC Complex, Co. Clare (Table 2.1). The hydrological dynamics and delineation of each catchment were beyond the scope of this project and focus was placed on the contrasting nutrient loadings associated with the general hydrology of the different karst aquifer types. The delineations of both of the SAC complexes and catchment areas are different; however, from this point on the mesotrophic/eutrophic Mixed Flow System Catchment linked to the Coole-Garryland SAC complex study area is referred to as "Coole Garryland" and the oligotrophic Epikarst Flow Catchment linked to the East Burren SAC Complex, Co. Clare is referred to as "East Burren".

Table 2.1: Turloughs selected for study from the Coole Garryland catchment and the East Burren catchment including site codes, grid references and current trophic sensitivities. 1 = Extremely highly sensitive to enrichment; 2 = Highly sensitive to enrichment; 3 = Medium sensitivity to enrichment.

Catchment Area Turlough sites	**Site Code**	**Grid Reference**	**Current Trophic Sensitivity**
Coole-Garryland Catchment		-	-
Coole Lough	CE	143025 204251	3
Garryland	GD	141580 203988	3
Hawkhill	HH	141144 202341	3
Caherglassaun	CG	141235 206225	3
East Burren Catchment		-	-
Cooloorta	CO	135550 196770	N/A
Lough Cuil Reasc	CR	134470 198230	1/2
Gortlecka	GT	131900 195000	N/A
Knockaunroe	KE	131317 193982	1

Four turloughs were selected for study from each catchment based on previous research conducted by the turlough research group in the Botany Department, TCD. The list of chosen sites is presented in Table 2.1 and sites are plotted in relation to hydrometric areas and River Basin Districts in Figure 2.1. It is clear from Figure 2.1 that sites located in the East Burren occur within the Western RBD and Shannon RBD and that sites in Coole Garryland occur in both the Shannon Estuary North and Galway Bay South East. Kilroy *et al.* (2005) highlighted that the study area in the eastern Burren/Gort Lowland region comprises highly karstified carboniferous limestone and as a result this area was identified as an area where groundwater is shared between river basin districts. The RBD boundary was originally closer to the boundary between the Galway Bay South East and the Shannon Estuary North. However, information from hydrogeological investigations in this area (Southern Water Global, 1998; Drew, 2003) indicates that there is a groundwater connection between Lough Bunny and the Cloonteen River, and therefore Lough Bunny was included in the Western RBD and the RBD boundary was moved south. The two catchments selected for study are hydrologically distinct according to Paul Johnston (pers. comm.) and he notes that the catchments are not only different in terms of their river systems but also in terms of individual zones of contribution. Turloughs in Coole Garryland have large zones of contribution, the turloughs being connected by a conduit system, whereas those in the Burren are perched and if they are connected it will be by epikarst (shallow groundwater flow) rather than conduits (deep groundwater flow). The zones of contribution of the East Burren are much smaller as a consequence (Paul Johnston pers. comm). Goodwillie (1992) also notes that a line drawn north-west south-east about 6km south west of Gort corresponds roughly with the watershed separating the northern Coole-Garryland Complex which drains to Galway Bay at Kinvarra, from the southern system of which the East Burren Complex is a part and which drains to the River Fergus.

The National Parks and Wildlife Service have assessed all turloughs designated as SACs for sensitivity to nutrient pressures to meet the waterbody characterisation objectives of the Water Framework Directive (WFD). Ellenberg Fertility Indices (Ellenberg, 1988; Hill *et al*,. 1999) were used to rank turloughs into three categories, according to the nutrient sensitivity of the dominant plant communities present at each site. Based on the Goodwillie (1992) turlough vegetation classification, an Ellenberg nitrogen score was assigned to each species in each of the 32 vegetation community types to give a general indicator of soil fertility, with higher scores indicating more fertile conditions. The score for all species within a community type were averaged to give a score for a community type. The proportion of low nutrient communities within each turlough was used to assign a trophic sensitivity to the site. The three trophic sensitivity categories are; 1 = extremely high sensitivity to enrichment (0.50-0.94 proportion of low nutrient plant communities), 2 = high sensitivity to enrichment (0.25-0.49 proportion of low nutrient plant communuties), 3 = medium sensitivity to enrichment (0.00-0.24

proportion of low nutrient plant communities). Sites located in Coole Garryland all were assigned a medium trophic sensitivity whereas available information for the sites located in the East Burren indicates an extremely high or high sensitivity to enrichment (Table 2.1). This information supports, to some degree, the assumption that turloughs within the two catchments have a contrasting trophic status. Four turloughs were selected from each catchment area based on accessibility, available trophic sensitivity information and history of previous research to provide a baseline against which to compare results. Individual turlough descriptions are a summary of information generated from MacGowran (1985), Coxon (1986), Goodwillie (1992) and personal observations.

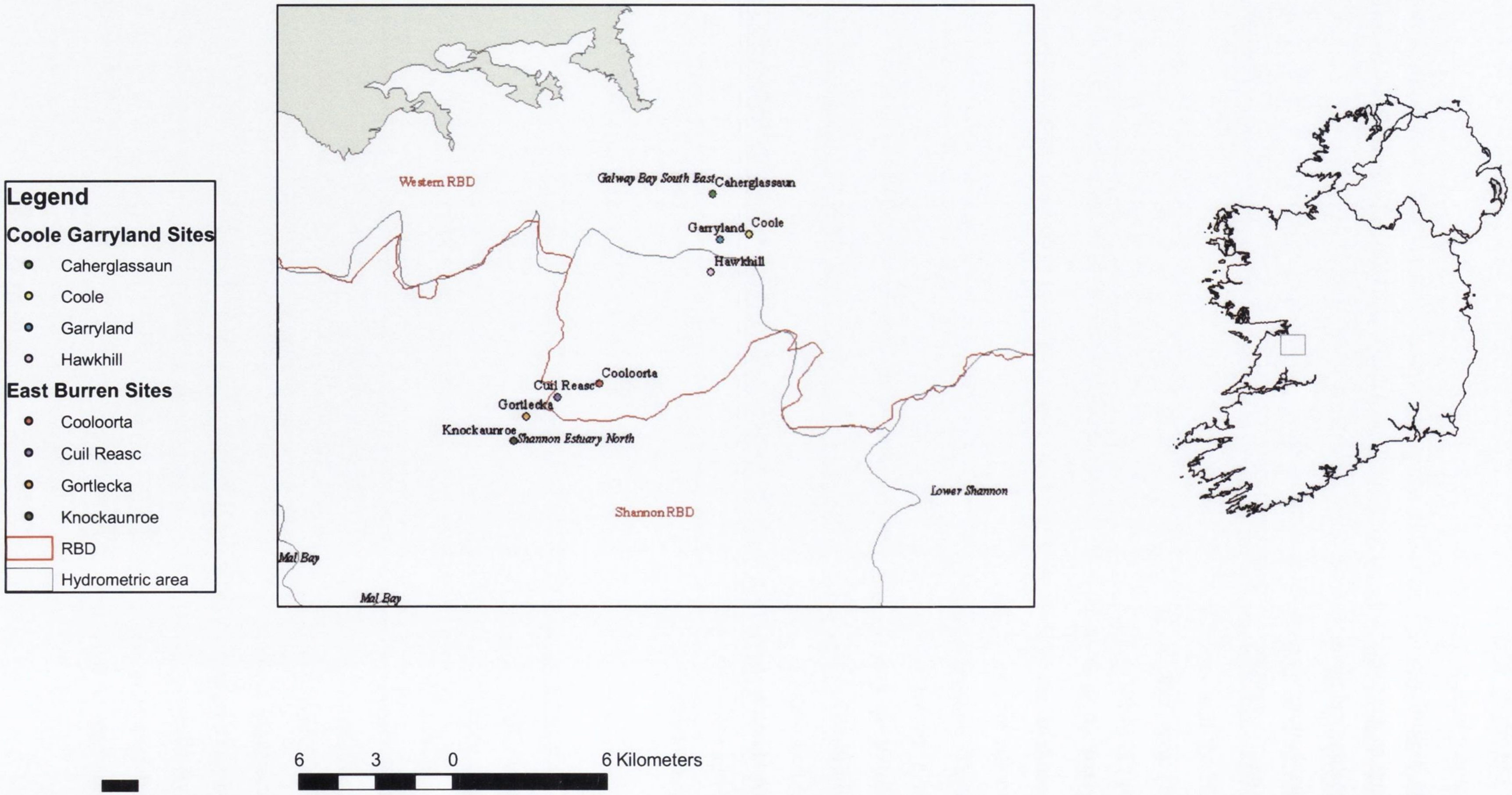

Figure 2.1: Location of turlough study sites in relation to national hydrometric areas and River Basin Districts.

2.2.2. Coole-Garryland Catchment

The Coole-Garryland SAC (Code 252) /SPA (Code 4107) is situated in a low-lying karstic limestone area west of Gort, County Galway (Figure 2.2.). In addition to turloughs, priority habitats in the area include limestone heath, limestone pavement and orchid-rich grasslands. The estimated catchment area is 31960 ha (Goodwillie, 1992) and the turloughs in this catchment occur on the Gort River system. This site is divided into two distinct parts, one based on the Coole River and lake and the other on a largely separate turlough in Newtown, though at times of high water both are linked together (Southern Water Global, 1998). This complex lies within a Mixed Flow System catchment where conduit karst occurs as deep as 40-50 m below ground. The Gort area was seriously damaged during extreme flooding in 1990 and consequently the area was subject to an in-depth hydrological study conducted by Southern Water Global. The document arising from this study provides detailed information on the hydrological conditions of the complex (Southern Water Global, 1998). The catchment receives water from the three rivers off the Slieve Aughty mountains and also, at high levels, from the Cloonteen River. It is therefore subject to large fluctuations every year and occasionally to extreme floods.

The turloughs located within this catchment are often moderately to heavily grazed, surrounded by improved pasture and receive mildly acidic iron-rich waters from the Slieve Aughty mountains (Goodwillie, 2001). According to The General Soil Map (Gardiner and Radford, 1980) parent material of this catchment area is limestone drift. The principal soil types are shallow brown earths and rendzinas and the associated soil types are grey brown podzolics, gleys and peats. Thick drift gives rise to rich farmland within this catchment area, but where the soil cover thins scrub-covered rocks become common place. In general the turloughs are surrounded by woodland, pasture and limestone heath. According to Goodwillie (1992) the most common vegetation types within turloughs from this complex are 5B *Potentilla reptans* (spp. poor), 6A Dry *Carex nigra* and 3W *Rhamnus* Wood.

2.2.2.1. Coole Lough (Inse Woods)

Plate 2.1: Inse Woods turlough looking towards the permanent water of Coole Lough in the Coole-Garryland catchment during Summer 2003.

This turlough (143025 204251) (Plate 2.1) is approximately 1.5 ha and is located on the eastern shore of the Coole Lough, 4 km north of Gort, in Co. Galway. Coole Lough is an extensive area which measures 4.5km from northeast to southwest and a maximum of 1.3km from east to west (Louman, 1984). The turlough has a gently undulating topography with a large, well defined swallow hole located in its centre and large boulders are located along the western edge. The turlough is bordered by woodland on all sides except the west which is bordered by the shores of Coole Lough in close proximity to where the Gort river enters the lake. The river rises in the Slieve Aughty mountains at about 300 m and flows onto the limestone plain before entering the lake and is responsible for silt deposition occurring on the lakeshores. The basin floods via a combination of lake water from Coole Lough, river water from the Gort River and groundwater which rises via the swallow hole.

The soils in this basin are gleys (Louman, 1984) which grade to river silts on the western edge. The main vegetation type within this basin is 5B *Potentilla reptans* (spp. poor) as defined by Goodwillie (1992). *Rumex crispus* and *Filipendula ulmaria* and *Potentilla anserina* dominate and species include *Viola persicifolia (*and hybrids with *V. canina)*, *Littorella uniflora*, *Limosella aquatica* and *Callitriche palustris*. Grazing by two horses was noted at irregular intervals throughout the project and hares have also been observed in the area. The general Coole area is grazed by cattle and sheep mostly as commonage (Goodwillie, 1992).

2.2.2.2. Garryland

Plate 2.2: Garryland turlough in the Coole-Garryland catchment during Summer 2003 showing woodland bordering the basin and a rasied ridge in the foreground.

Garryland (141580 203988) (Plate 2.2) lies in the western area of the catchment and is partly a collapse feature with large boulders and rocks around the south-western end. The turlough consists of a simple basin of 20.4 ha with a spur of higher ground from the south shore which gives the turlough a horseshoe shape. Topographically the basin is interesting for its depth and slopes of up to 20 degrees. Boulders are a feature of the base of most slopes and a few smaller rocks extend onto the predominantly flat floor (Plate 2.2). Most of the land is ridged and therefore was cultivated at some time (Goodwillie, 1992). The main water supply probably comes from the Coole/Newtown area and in flooded conditions these two areas are linked together overground. Williams (1964) puts Garryland on a small side branch off the main valley of the Gort River, so it may have an independent catchment (80-100 ha) in some years. A shallow U shaped water channel marks the floor linking two semi-permanent ponds.

The basin substrate is a combination of mixed drift material with silty surface layers and some shallow peat. The mineral soil promotes two main communities 5B *P. reptans* (spp. poor) and 6A Dry *C. nigra* and wetter ground holds 9B *Eleocharis acicularis* which is a speciality of Garryland. There are two permanent ponds in the extreme west and south and these contain many aquatic species including *Callitriche brutia*.

Woodland is a feature of the whole Coole Garryland catchment and occurs in Garryland as *Crataegus monogyna/Rhamus catharticus* mix at the northern end and as a *Quercus robur/Fraxinus excelsior* mix at the southwest corner. Species of note include *Lythrum portula*, *Viola persicifolia*, *Ceratophyllum demersum* and *Eleocharis acicularis*. Sheep and cows are numerous on the grassy areas and overgrazing is severe, creating difficulties for plant identification.

2.2.2.3. Caherglassaun

Plate 2.3: Caherglassaun turlough in the Coole-Garryland catchment during Summer 2003 showing the rocky, infrequently flooded upper area in the foreground, permanent lakewater and drift smoothed slopes in the background.

Caherglassaun Lough (141235 206225) (Plate 2.3) occupies an area of 41.8 ha and lies in the north-western area of the Coole-Garryland complex. The basin has an even, drift smoothed slope on the south-east side but rises abruptly on the north-west in a series of rocky steps. The site includes a permanent lake, fed by a stream from the south-west (Goodwillie, 1992) which has a rocky western shore, with gravel and mud elsewhere and the turlough surrounds this lake. Williams (1964) suggested that this turlough lies in the main channel of the Gort River as it flows from Coole Lough to Kinvarra. The upper part of the karst in this area allows a direct connection with the sea for Caherglassaun Lough (5km from Kinvarra) where there is measurable daily fluctuation of water level caused by tidal pressure on the reservoir of water, which is most obvious at low water levels.

Parent materials within the basin include sand and lacustrine sediments and the predominant soil types include organic rendzinas, gleys and sandy gleys and muds (MacGowran, 1985). The main part of the turlough has soil derived from glacial drift so that it is stony without significant amounts of marl or peat (Goodwillie, 1992). The lake however collects some finer sediment and a silt delta is built by the inflowing stream at the south-west end. The predominant community on the drift soils is 5B *P. reptans* (spp. poor) and it covers most of the land that is regularly flooded below the uppermost 2A *Lolium* Grassland or 2B Poor Grassland. According to Goodwillie (1992) the extent of the *Eleocharis acicularis* (9B) community is the second only to Garryland. The more aquatic vegetation of this basin is unusual since it is subject to the daily tidal flooding mentioned above. The more noTable species are *Limosella aquatica*, *Viola persicifolia*, *Rorippa islandica* and *Rorippa sylvestris*, *Ceratophyllum demersum* and *Lythrum portula*. Most of the area is grazed by cattle or sheep and while the intensity is greatest on the south-east side, there are often cattle on the west around the rocks.

2.2.2.4. Hawkhill

Plate 2.4: Hawkhill turlough in the Coole-Garryland catchment during Summer 2003 showing surface drainage to the turlough on the southwest shore and rocky slopes surrounding the flat turlough floor supporting a permanent pond.

This turlough (141144 202341) (Plate 2.4) is a roughly elliptical, small (< 10 ha) depression, with the long axis running east west. To the east, south and west the ground slopes steeply (3-15°) while to the north there is a vertical outcrop of bedrock. Large boulders as well as smaller outcrops are scattered over most of the ground.

An estavelle is located at the base of this outcrop which in summer receives a stream which rises in the southwest of the basin and feeds a permanent pond separated from the estavelle by boulders. This turlough floods in winter to a depth of 8 m, reaching sometimes 10 m and at very high flooding there has been overground connection with Newtown to the east.

As this turlough is less than 10 ha it was excluded by studies conducted by Coxon (1986) and Goodwillie (1992). MacGowran (1985) provides the only comprehensive ecological survey of the basin. The parent materials in the basin grade from marl deposits over till on the upper and middle slopes to lacustrine sediments in the lower basin areas. The main soil types include rendzinas on the upper slopes which grade to alluvial gleys and peaty alluvial gleys towards the very bottom slope of the basin, just above the level of permanent water. Using the indicator species determined by Goodwillie (1992), the dominant vegetation type on the upper slopes is 5B *P. reptans* (spp. poor) and 9B *Eleocharis acicularis* in the lower basin areas. *Viola persicifolia* and *Rubus caesius* are well represented in the upper areas of the basin and *Rorippa spp.* and *Polygonum* spp. occur where poaching is heavy. MacGowran (1985) provides an account of the turlough`s grazing history and notes that the basin is divided by walls into several fields, the lower areas of which were never grazed and the larger higher ones were moderately grazed. An electric fence was erected approximately two years ago excluding cattle which has had a noTable impact on the vegetation. The high ground to the west is occasionally treated with fertiliser and land adjacent to the turlough is highly fertilised.

2.2.3. East Burren catchment

This SAC (Code 1926) covers 18,800 hectares of the Burren region in north Co. Clare and a small part of southwest Galway (Figure 2.3.). Drew (1975) states that the Burren is divided into two parts, the western Burren with partial shale cover and the eastern Burren composed wholely of limestone. The area encompasses a complete range of limestone habitats including limestone heath, orchid-rich grassland and is dominated by limestone pavement. In places the pavement joints are often enlarged by solution to produce a classic clint and grike landscape (Drew, 1975). There are 15 turloughs within the East Burren SAC and the four turloughs selected as study sites are located around Mullach Mor and occur within the Fergus river system catchment (Goodwillie, 1992). Turloughs in this catchment have significant amounts of bedrock exposed in the basin, while marl accumulation is common either in the present or in the past (Coxon, 1986).

Drew (1975) provided a review of the landforms of the Burren. The eastern Burren landscape consists of a relatively flat summit plateau at 200-300 m, broken by deep dry valleys generally oriented along the north-south jointing and very large closed depressions, including turloughs, often oriented east-west. The hydrology of the turloughs in this catchment is less well understood than those of the Coole-Garryland complex due to its more complex nature and lack of research. In summary, Drew (1990) concluded that storage within the limestone aquifer is very limited and rates of groundwater movement are rapid. The Burren differs from other karstic regions in the complexity of its hydrology, particularly in the very large number of small springs. For these reasons it cannot be stated that the four turloughs chosen for study are certainly hydrologically linked.

According to The General Soil Map (Gardiner and Radford, 1980) the parent material of the East Burren Complex is composed mainly of limestone. The principal soil type is rendzinas with outcropping rock and the associated soil types are lithosols and shallow brown earths. Goodwillie (1992) states that turloughs in this area are very lightly grazed and land-use within the surrounding catchment area is of a moderate intensity. Goodwillie (1992) surveyed six basins within this complex and the three most common vegetation types recorded included 6B Wet *Carex nigra*, 5D Sedge Fen and 9C Marl Pond.

2.2.3.1. Knockaunroe

Plate 2.5: Knockaunroe turlough in the East Burren catchment during Summer 2003 showing extensive limestone pavement surrounding turlough.

Knockaunroe (Plate 2.5) (131317 193982) occupies a large shallow, flat area (42 ha) and is situated in the flat limestone pavement southwest of Mullach Mor. It lies in a narrow depression that opens out towards the east and is physically diverse with rock outcrops and some semi-permanent water. The northern end is surrounded and crossed by ridges of bare rock, trending NE-SW. To the west and south there is a thin cover of soil on the rock and the turlough breaks through a low ridge to fill a subsidiary basin. The turlough is totally dependent on ground water as there is no river inflow into the basin and it is the only basin in this area that is thought to be epikarst with a high degree of certainty. Swallow holes occur particularly on the northern shore as enlarged cracks in the pavement. Hydrological data recorded by Byrne (1981) indicated that the period of greatest inundation is October to February, while the driest period is April to July, and water stays late in the basin. There is usually a large lake in the northern half into June (Goodwillie, 1992).

It seems likely that the northern basin was once entirely filled with peat whereas the southern basin seems less peaty with a broad band of peat down the middle. The peat is 1m thick where it remains intact (MacGowran, 1985). The predominant vegetation community at Knockaunroe is 9C Marl Pond. Blocks of peat stand out covered by 4D Schoenus Fen, which is dominated by *Schoenus nigricans* and 7B Tall Sedge, characterised by tufts of *Carex elata.* Knockaunroe is the only turlough in which *Utricularia minor* and *U. intermedia* were found and it also contains most of the Burren specialties, for example *Frangula alnus*, *Potentilla fruticosa*, *Viola persicifolia* and *Teucrium scordium.* Around areas of permanent water species such as *Potamogeton gramineus*, *P. polygonifolius*, *Myriophyllum alterniflorum* and *Eleogitan fluitans* indicate the oligotrophy of the highly calcareous water. Peat cutting was extensive in the past and influences the mosaic of plant communities within the basin and the depth of flooding. Cutting has exposed the underlying marl in many places and also allowed marl to reform on the lowered peat surface. There is little grazing of the unpalaTable herbage though the basin is open to cattle from most sides and there is only one adjacent field at the southwest end of the northern basin.

2.2.3.2. Gortlecka

Plate 2.6: Gortlecka turlough in the East Burren catchment during Summer 2003 showing extensive limestone pavement surrounding the turlough.

This turlough (Plate 2.6) (131900 195000) is located 1.8 km SSW of Mullach Mor Co. Clare and is approximately 3 m deep and 2 ha in area. This is a small sheltered depression with steep rocky sides to the south west and gently sloping to the north east so that it is almost flat bottomed. The basin is surrounded entirely by limestone pavement. It is at the same elevation as the adjacent Knockaunroe basin though it appears to be flooded for shorter periods than its neighbour (MacGowran, 1985). Once the basin has drained in the early summer period it remains dry until the autumn unless there is heavy rainfall for a sustained period.

It appears that cattle are regularly driven through the site but are only occasionally left there to graze. The turlough is also grazed by feral goats and hares. The turlough was not surveyed by Goodwillie in 1992 but according to his vegetation classification system the vegetation is dominated by sedge species but lacks aquatic vegetation types typical of turloughs in this catchment. Rare species occuring within this turlough include *Frangula alnus*, *Potentilla fruticosa*, *Viola persicifolia*, *Teucrium scordium* and *Thelypteris paulstris*.

2.2.3.3. Cooloorta

Plate 2.7: Cooloorta turlough in the East Burren catchment during Summer 2003 showing extensive limestone pavement, interspersed with *Calluna vulgaris*, surrounding the turlough. The lower turlough area rarely dries out and supports stands of *Carex elata*, *Schoenoplectus lacustris* and ***Cladium mariscus.***

This turlough (Plate 2.7) (135550 196770) lies approximately 4 km to the east of Mullach Mor and is approximately 20 ha in area. The basin is shallow (approximately 1-2m deep) and is surrounded by limestone pavement. The basin retains water for most of the summer months and personal observations suggest that, of the four basins studied in this complex, this basin tends to recharge most rapidly in response to heavy rainfall. A series of small lakes, including Castle Lough, Skaghard Lough and Travaun Lough, lie to the North and East of Cooloorta. These lakes are connected hydraulically by over ground streams and may also have underground connections with each other and with Cooloorta.

This turlough contains a diverse range of vegetation types. The northern area is dominated by stands of *Cladium mariscus*, *Schoenoplectus lacustris* and *Phragmites australis*. The southern basin area is dominated by drier vegetation types (Goodwillie, 1992) including large areas of 3B Sedge Heath dominated by *Calluna vulgaris*, 3C Limestone Grassland and 7B Tall Herb dominated by *Carex elata*. The major substrate types include organic rendzinas, peats and marls. This basin is moderately grazed and during the summer months poaching around areas of the basin retaining water is severe.

2.2.3.4. Lough Cuil Reasc

Plate 2.8: Lough Cuil Reasc turlough in the East Burren catchment during Summer 2003 showing extensive limestone pavement surrounding this shallow flat turlough which rarely dries out completely during the summer months.

Cooloorta turlough (Plate 2.8) (132881, 174471) lies less than 1km to the south of Mullach Mor and is surrounded by limestone pavement. The entire area of the turlough is flat and very shallow (< 1m) and fluctuates with flood water during the summer months. This basin is dominated by peaty soil types and the dominant vegetation types including 6B *Wet C. nigra*, 6D Peaty *Carex nigra*, 5D Sedge Fen and 4D *Schoenus* Fen reflect this. A shallow ditch runs NW through the centre of the turlough in a north westerly direction and the basin is lightly grazed by horses, cattle and goats.

2.2.4. Selection of sampling sites and sample collection

Studies of soil nutrient variation usually use soil type maps to formulate sampling strategies but soil type maps do not exist for turloughs. However, previous studies (MacGowran, 1985; Coxon, 1986, Goodwillie, 1992) have concluded that different soil types are located in the upper, middle and lower zones of turloughs and that these elevation zones are broadly related to changes in vegetation type. A stratified random sampling approach was used and changes in vegetation and topography were used to delimit upper, middle and lower general elevation zones. Upper zones experience infrequent flooding and are associated with the shortest annual duration of flooding. These areas are characterised by the occurrence of (often stunted) woody species such as *Crataegus monogyna, Potentialla fruticosa, Calluna vulgaris*. Lower zones are frequently flooded and experience the longest duration of annual flooding and middle zones experience varying degrees of flooding duration. The lower zones areas are often associated with reed beds and marl pond areas, and often retain pools during the summer months. These zones broadly represent the within-site spatial variation in hydrological regime but should be considered with caution in the absence of topographical survey maps and hydrological data. Upon entering a site the water`s edge and turlough upper edge (delimited by the occurrence of surrounding woody vegetation) defined the extent of the sampling area. Samples representing the upper area were taken in close proximity to the surrounding woody vegetation and samples representing the lower areas were taken in close proximity to the waters edge. Samples representing the middle zones were taken from midway between the upper turlough limit and waters edge. The water level at the time of sampling had a major influence on the sampling strategy but given the dynamic nature of the habitat this situation was unavoidable. Vegetation maps produced by Goodwillie (1992) were used, where available, to indicate the occurrence of upper and lower elevations and from this point forward, reference to vegetation types in the text relates to those defined via this study. Vegetation maps were available for Garryland, Caherglassaun, Coole Lough and Knockaunroe (Appendix A). The scale of these maps is large however (1: 16250) and often vegetation types grade gradually into one another rather than abruptly changing as indicated by the maps. The number of samples collected from each elevation zone within each turlough are presented in Table 2.2.

Sample collection was conducted in April and August 2003. At each sampling point, approximately 15 cores were taken using a standard Teagasc (The Irish Agriculture and Food Development Authority) corer to a depth of 10 cm from a 1m^2 quadrat and bulked to provide a composite sample sufficient for the range of analyses. A trowel was used to collect samples from the wetter turlough floor areas as it was not possible to use the soil corer due to weak soil structure.

Traditionally, sampling has been conducted at depths of 0-30 cm reflecting the rooting depths of plants and thus nutrient extraction zone. Sampling here was conducted to a depth of 10 cm due to the extremely shallow nature of some turlough soils. Vegetation was recorded within each quadrat using Domin scores (Kent and Coker, 1992). An example of the vegetation recording sheet is presented in Appendix C which was generated from Goodwillie (1992).

Table 2.2: Table showing number of samples collected from the upper, middle and lower elevation zones within each turlough. CE = Coole turlough, GD = Garryland turlough, CG = Caherglassaun turlough, HH = Hawkhill turlough, KE = Knockaunroe turlough, GT = Gortlecka turlough, CO = Cooloorta turlough, CR = Lough Cuil Reasc turlough.

	Coole-Garryland				East Burren			
	CE	GD	CG	HH	KE	GT	CO	CR
Upper	2	2	2	2	2	3	2	1
Middle	2	2	4	3	5	3	2	
Lower	5	3	2	2	6	2	2	1

2.2.5. Determination of soil types

Finch (1971) stated that in mapping their distribution in any area, the soils can be classified on a broad scale, into great soil groups, each consisting of a collection of closely related soil series. The poorly developed nature of turlough soils and their shallowness made horizon determination difficult so soil samples were assigned to broad soil groups using soil depth, soil colour, pH, organic matter type and content, calcium carbonate content and soil texture. An example of the data recording sheet used for soil descriptions is presented in Appendix B. Soil depth was measured using a 1m soil peak. Soil colour (soil matrix, mottling and shell marl) was described using Munsell Soil Colour Charts. The abundance, size and contrast of mottles and the sharpness of mottle boundaries were described according to criteria in Hodgson (1978) (Table 2.2 a).

Table 2.2a: Abundance, size and contrast of mottles and sharpness of mottle boundaries used for soil colour descriptions (after Hodgson (1976).

Abundance	Size	Contrast	Boundaries
None	Extremely fine (< 1 mm)	Faint (indistinct)	Sharp
Few (2% of matrix)	Very fine (1-2 mm)	Distinct (readily seen)	Clear
Common (2-20% of matrix)	Fine (2-5 mm)	Prominent (conspicuous)	Diffuse
Many (20-40% of matrix)	Medium (5-15 mm)		
Very many (>40% of matrix)	Coarse (> 15 mm)		

Soil texture was determined using hand textural analyses (Ball, 1986; see Appendix D). Soil textural analysis using Particle Size Distribution techniques were not used as studies conducted by Styles (2004) on high organic matter soils noted that organic matter interferes with the textural analyses by flocculating with clay and silt particles. The nature of organic matter content was described as either **Semi-fibrous** partly decomposed fibres which are largely destroyed by rubbing or **Fibrous** containing large amounts readily identifiable plant remains. The abundance of shell marl flecks was also described (None, Few (<2% of matrix), Common (2-20% of matrix), Many (20-40% of matrix) Abundant (>40% matrix). In the absence of soil maps, the characteristic features of the main turlough soil types, including information on the location from which samples were taken and the associated vegetation types, were collated from previous studies (MacGowran, 1985, Coxon, 1986). This information, along with soil classification information in Finch (1971), was used to classify the soil samples into broad soil groups. The diagnostic soil type characteristics relevant to the turlough situation follow.

2.2.5.1. Rendzina Group

MacGowran (1985) recorded variants of rendzinas at the highest levels in turloughs, on both diamicton and bedrock. These shallow soils are usually not more than 50 cm deep, derived from parent material containing over 40-50% carbonates (Finch, 1971). In the absence of investigations of parent material type, it must be acknowledged that this soil group may constitute a heterogenous assemblage of shallow soils rather than typical rendzina soils. According to MacGowran (1985) the better quality rendzinas had no sign of gleying with light structure and texture, occurring on level to fairly steeply sloped ground. A distinction is made between rendzinas on limestone derived diamicton and on limestone pavement. According to Finch (1971) rendzinas occurring over limestone diamicton are classed as Kilcolgan Series, which include shallow soils (less than 38 cm) with high pH values with textures varying between clay loam and gravely sandy clay loam. The vegetation associated with this soil type is either species rich grassland or the trees and shrubs of unmanaged grassland (MacGowran, 1985). Rendzinas found over limestone bedrock are classed as Burren Series which are associated with a flat or steep topography. Organic matter content ranges from 20-40% and texture is clay loam, friable and of high pH status. These soils are never more than 23cm deep (Finch, 1971). The vegetation associated with this soil type include typical turlough fringe species such as *Crataegus monogyna* and *Rhamus catharticus*, low growing stunted trees, shrubs, grass and sedge dominated swards (MacGowran, 1985).

2.2.5.2. Gley Group

Gleys are soils in which the effects of drainage impedance dominate and which have developed under conditions of intermittent water-logging. Where the gley condition results from a high water-Table the soils are referred to as groundwater gleys. The mineral horizon of gleys are usually grey (or bluish-grey in more extreme cases) with distinct ochreous mottling much in evidence. Gleys generally have weak structure, are not friable, and in the wet state tend to become very sticky (Finch, 1971). According to Finch (1971) Gleys have a wide range of soil depths but those occurring on limestone heath or limestone drift are generally less than 30 cm. Daly *et al.* (2001) found that the organic matter content associated with Gley and Peaty Gley soils consistently ranged from 12.1-20% (by weight) and 20.1-30% respectively and the OM range from 12.1-30% is taken as a diagnostic characteristic of turlough Gleys. The vertical range involved is from about the mid-level to the turlough floor, or just above the floor if there is a permanent stream, lake or marsh. The vegetation of gleys includes *Agrostis stolonifera*, *Potentilla reptans* and *Ranunculus repens* which are near constant or dominant, and *Carex nigra*, *Mentha spp.*, *Leontodon autumnale*, *Galium palustre* are usually well represented (MacGowran, 1985).

Soils on the middle and lower slopes with soil depths ranging between 23 and 30cm and organic matter content ranging between 12 and 30%, with gleying in the upper surface, were classified as Gleys.

2.2.5.3. Alluvial Soils

These soils are derived from alluvial deposits and turlough alluvial soils occur on lacustrine deposits, which occur in landscape depressions which were originally the sites of glacial or post-glacial lakes (Finch, 1971). Most of these soils are very immature and show little or no profile development and are differentiated on the basis of such factors as origin and composition of parent material, texture and drainage (Finch, 1971). Shallow soils (< 30 cm) which lacked gleying and had a silty texture were classified as Alluvial soils.

2.2.5.4. Fen Peats

Peats are characterised by a high content of organic matter (> 30%) and by being at least 30cm in depth. Fen peat forms under the influence of base-rich groundwater and is composed mainly of the fibrous remains of reeds, sedges and other semi-aquatic or woody plants (Finch, 1971).

2.2.5.5. Marls

The term marl when used for pure calcareous lacustrine deposits is often prefixed by a word indicating the major organic-derived component i.e. shell marl. Lake or shell marl is partly formed when the shells of gastropods and other fresh-water molluscs which dwell in the calcium rich lakes, accumulate on the bottom of the lake, and form a thick layer of lake marl. This marl is very high in $CaCO_3$ (>70%) , white to light grey or light brown in colour, with a very high pH. Turlough marls are also composed of calcite deposits due predominantly to supersaturation caused by the loss of excess carbon dioxide from floodwater to the atmosphere (Coxon, 1994). Calcareous skeletons of fauna are a major component of turlough marl but the deposit is primarily composed of inorganic calcite crystals (Coxon, 1986).

2.2.5.6. Peat-Marls

This substrate type represents the mid-point of the continuum from marl to peat and has a characteristic calcium carbonate content of 55-70% and an organic matter content of 10-25% (Coxon, 1986).

2.2.6. Sample preparation for laboratory analyses

Soils were stored in polythene bags placed in cool boxes with frozen ice packs prior to preparation and analysis. Collected samples returned to the Centre for the Environment Laboratories, TCD were homogenised (thoroughly mixed by hand) and one sub-sample of moist soil was taken from each sample, sieved through a 4 mm brass sieve and analysed for pH and soil moisture content. The remainder of each sample was oven dried at 35°C for 48 hours, ground with a mortar and pestle, sieved (2 mm mesh) and stored at room temperature in envelopes.

Dried samples were analysed in duplicate/triplicate for a range of soil nutrient and nutrient-related variables including organic matter (OM), calcium carbonate ($CaCO_3$), total nitrogen (N_t), total phosphorus (P_t), Morgans P (P_m), desorbable P (P_{feo}), total potassium (K_t), total iron (Fe_t), total magnesium (Mg_t) and total calcium (Ca_t). Total and desorbable P were selected for analysis to provide information on both the potentially available and readily available forms of soil P respectively. Morgans P was also selected for analysis as this method is the widely used agricultural P fertility assessment.

2.2.7. Laboratory analyses

Soil Moisture Content (Allen, 1989): 10g of soil were taken from each sieved, homogenised sample, placed into foil trays, weighed and left in an oven at 105°C for 24 hours. The trays were then removed from the oven, allowed to cool and reweighed to calculate moisture loss which was expressed as a percentage.

Soil pH (Allen, 1989): Estimations of pH were on an approximately 1:2 suspension of moist soil and double-distilled water (DDW). The suspension was mixed vigorously, allowed to stand for thirty minutes and pH determined using a Jenway 3030 calomel electrode and meter after 2 minutes of equilibration with the soil solution. Two separate measurements were made for each mixed soil sample. The arithmetic mean was obtained via the antilogarithms of the readings.

Organic matter and carbonates (Allen 1989): Organic matter (OM) was measured as a percentage weight loss following ignition at 550°C. Approximately 1g of oven-dry soil was accurately weighed (to four decimal places) and placed in a muffle furnace brought up to 550°C for four hours. After being left to cool in a dessicator, soils were re-weighed and percentage weight loss calculated.

Carbonate content was estimated as a percentage weight loss following loss on ignition by further ignition at 1000°C. The non-calcareous inorganic content (mineral sand/silt/clay fraction) of each sample was calculated using the OM and $CaCO_3$ contents.

Total nitrogen (N_t) (Verado *et al.*, 1990): Approximately 0.2 g of each sample was accurately weighed to 4 decimal places into a small tin cup and loaded into a LECO CNS-1000 elemental analyser.

Total phosphorus (P_t), total calcium (Ca_t), total iron (Fe_t) and total potassium (K_t) in soil: Samples were weighed out to approximately 0.5g in clean dry microwave vessels and recorded to four decimal places. 10 ml of 69% Nitric Acid was added to each vessel and one blank was run during each digest using a MDS 2000 microwave. After each digest the samples were filtered into a 25ml volumetric flask using Whatman No. 1 filter paper, made up to volume using DDW and stored for further elemental analysis. Total P was determined colorimetrically by a phosphomolybdate blue method (Murphy and Riley, 1962) in an aliquot of the HNO_3 solution diluted 1:50 in DDW. This was found to be the optimum dilution in order to prevent acid interference with the reagent. The absorbance of the samples was read at 882 nm on a Shimadzu UV 1601 visible spectrophotometer. Total calcium, magnesium, iron, manganese and potassium in the filtered soils samples were analysed by Flame Atomic Absorption on a Perkin Elmer Spectrometer (model 3100). Total potassium in the filtered leaf samples was also determined using this method. Samples were diluted with DDW when necessary to bring them within the range of standards used.

Morgan P (P_m) (Morgan, 1941): The Morgan extractant was made up by dissolving 56g of sodium hydroxide (NaOH) in 1.5 litres DDW, to which 144 ml of glacial acetic acid was added, and the solution made up to 2 litres. The pH was then adjusted to 4.8 using NaOH. 30 ml of this reagent was added to 6ml of dried soil (measured using a scoop) in polypropylene bottles. The bottles were shaken at 120 oscillations per minute for 30 minutes, then the solutions were filtered through Whatman ® no. 2 filter papers prior to MRP analyses (Morgan, 1941).

Table 2.2: Soil Morgan P ranges for the four P indices used by Teagasc to categorise soil P status.

Index	Status	Morgan P mg l^{-1}	
		Mineral	Peat
1	Low	0.0-3.0	0-10
2	Medium	3.1-6.0	11-20
3	High	6.1-10.0	21-30
4	Very high	>10	>30

Desorbable P (P_{feo}) (van der Zee *et al.*, 1987): Desorbable phosphorus was determined by extraction with Iron Oxide-Impregnated filter paper. The principles of this extraction are that iron oxide impregnated on filter paper strips provides sites to specifically sorb P from soil solutions. In the presence of a sufficient quantity of impregnated iron oxide, the P concentration in solution can be kept negligibly low to facilitate continued P desorption from the soil. The rate of P desorption is first order and is controlled by the quantity of reversibly sorbed P. The amount of P sorbed on the iron oxide impregnated strips over an extended period of time was used to index the P availability in soils. Iron-oxide impregnated paper strips were made according to Menon (1988). One 10 x 2 cm strip was placed in each 125ml polypropylene bottle containing 40 ml 0.01M $CaCl_2$ and 1 g dried soil, and the bottles left shaking at approximately 80 oscillations per minute for 16 hours. The iron-oxide strips were then removed, rinsed with DDW to remove adhering soil particles, and shaken for 2 hours with 40 ml of 0.2M H_2SO_4 to extract all sorbed P. Molybdate Reactive Phosphorus was then analysed in an aliquot of the H_2SO_4 solution diluted 1:5 in DDW (Daly, 2000) using the Murphy and Riley (1962) method.

All analyses used Analar R grade reagents. All analyses conducted to assess the general nutrient status of each basins were conducted in triplicate where possible. Some samples collected from the wetter or peaty turlough areas reduced considerably upon drying and sieving and in some limited instances it was only possible to make a single measurement on a composite sample. All analyses conducted on the samples were analysed in duplicate with the exception of pH and soil moisture. All glass and plastic ware used in analyses were thoroughly washed using DDW after every analysis, and periodically acid washed. Filters were washed with sample prior to filtration of soil solution extracts. Analytical accuracy for elemental concentrations in soil extract and digest solutions was ensured for all analyses through the use of quality control (QC) standards. These QC standards were made by the laboratory technician from separate stock to calibration standards and it was ensured that their measured concentrations always fell within an accepTable range of the true value (± 3%). Actual soil extraction methods were not validated using outside reference materials.

2.2.8. Expression of concentrations

Jeffrey (1970) found a strong relationship between soil organic matter content and bulk density (BD: the dry weight of a given volume of soil) on eighty 0-5cm deep soil samples from a range of soil types in Australia and England: BD=1.482-0.6786logX (r=0.905) where BD is expressed as g/ml and X represents percentage ignition loss at 550°C (OM content). Jeffrey suggests that comparisons of soil chemical analyses are frequently best made on a soil volume basis. This is particularly true of site comparisons for ecological purposes, where soil bulk density may vary considerably. Soil bulk density is however rarely presented amongst analytical data in ecological literature and it is a matter of common experience that its estimation is not always convenient or possible such as in the wet soils of the turlough environment. Although the organic matter content of a soil is not the sole determinant of its density, it has been shown to be a reliable empirical predictor. Owing to the range of peat and mineral soils in this study, there is a wide range of BDs, with the consequence that expressing concentrations on a weight basis compares hugely differing volumes of soil. Consequently, soil nutrient data are presented and compared on a volume basis (mg l^{-1} soil) using the estimated soil bulk densities.

2.2.9. Data preparation and analysis

Data are presented in Appendix E. Mean values of sample replicates were calculated for multivariate analyses whereas individual sub-sample measurements were included in analyses of variance (ANOVA). Summary statistics including mean, median, standard deviation and range were generated using Data Desk® 6.0. Data were first examined for normality, and where necessary, logarithmically transformed in Data Desk for parametric analyses. Details of specific designs, including transformations, are listed with their results.

2.2.9.1. Comparison of soil nutrient-related properties within and among contrasting catchment types.
An analysis of variance for a nested design (i.e. turloughs nested within complexes) with interaction effects for sampling location (upper, middle and lower) within turloughs was used to investigate variation in soil nutrient status between catchments. Replicates analyses were included in the nested design. Nested factors are usually random but in this case turloughs were designated as fixed factors as they were not randomly chosen from all turloughs within each catchment. One-way ANOVA with interaction effects for sampling location within turloughs was used to examine variation among turloughs within each catchment.

2.2.9.2. Comparison of nutrient status among turlough soil types characteristic of each catchment.

One-way ANOVA and Bonferroni post-hoc tests (DataDesk 6.0) were used to examine variation among the most common soil types within each catchment. Skewed variables were log transformed to achieve approximate normality.

2.2.9.3 Relationships between vegetation types representative of two contrasting catchment areas and soil nutrient properties.

The analysed dataset consisted of 60 releves sampled from the East Burren catchment and the Coole Garryland catchment. Three complementary statistical techniques were used to analyse the dataset. Analysis was conducted using PC-ORD 4 (MjM Software, Oregon). The main method selected for grouping the data into vegetation types was hierarchical, polythetic, agglomerative cluster analysis. From a data matrix of n samples x p species, an n x n distance matrix is calculated by measuring the dissimilarity (or similarity) between each pair of samples. The most similar samples which are selected using a predetermined criterion of minimum distance (linkage method), are merged into a group and their attributes are combined. The procedure is repeated n-1 times until the samples have been merged (clustered) into two groups, with the results being displayed as a dendrogram (McCune and Grace, 2002). Quantitative Sørensen (Bray-Curtis) was selected as the distance measure, as it has been shown to be one of the most effective measures for ecological community analysis, being less prone to exaggerating the influence of outliers and retaining greater sensitivity with heterogeneous datasets (McCune and Grace, 2002). Flexible beta was used as the linkage method with β=-0.25 (Lance and Williams, 1967). Indicator species analysis (ISA; Dufrene and Legendre, 1997) was used as an objective tool to determine at what level the dendrogram resulting from the hierarchical clustering should be cut, i.e. what is the optimal number of final groups. ISA produces percentage indicator values (IndVals) for species and works on the concept that for a predetermined grouping of samples, an ideal indicator species will be found exclusively within one group and will be found in all the samples in that group. IndVals are thus a simple combination of measures of relative abundance between groups and relative frequency within groups. At any given level of clustering, species are assigned to the group for which their IndVal is maximal; the significance of this assignment is tested using Monte Carlo randomisations. Dufrene and Legendre (1997) concluded that ISA was more sensitive at identifying indicator species than TWINSPAN and also suggested that this method could be used as a stopping rule for clustering, as IndVals will be low when groups are too finely or too broadly defined, peaking at some intermediate, most informative level of clustering. ISA was run on the output from the hierarchical clustering cycles yielding 2-30 groups with 1000 randomisations used in the Monte carlo tests. Number of significant indicators ($p \leq 0.05$) and sum of IndVals for significant indicators were used as stopping criteria (Dufrene and Legendre, 1997; McCune and Grace, 2002).

Non-metric multidimensional scaling (NMS) was used to illustrate the relationships between releves. This iterative ordination technique is particularly well suited for analysis of ecological community data as it works well with non-normal datasets, allows the use of non-Euclidean distance measures, and does not assume that species have linear or unimodal responses to environmental gradients (McCune and Grace, 2002). Being based on ranked distances, NMS is less prone to distortion due to outliers. For ecological analysis, NMS has been recommended over the more widely used Detrended Correspondence Analysis (DCA) method which has been seriously criticised by several authors (e.g. Minchin, 1987; Legendre and Legendre, 1998; McCune and Grace, 2002). The `slow and thorough' option in PC-ORD was used with Quantitative Sørensen (Bray-Curtis) distance and varimax rotation. The use of this distance measure permits ready comparison of the results with those of the hierarchical cluster analysis. Hence the ordination was run on a matrix of 60 releves and 70 species. Monte Carlo tests using randomised data were used to calculate the probability of real date having less stress (and hence some structure) than randomised data. The following parameter protocol for the NMS ordination was used: number of axes = 6; runs with real data = 40; stability critierion = 0.00001; iterations to evaluate stability = 15; maximum number of iterations = 400; step down in dimensionality = 1; initial step length = 0.2; starting coordinates = random; Monte Carlo test runs = 50. Infrequently occurring species were not deleted from the dataset as some were dominant where they occurred. The significance test for Kendall Tau correlations of soil variables with NMS ordination axes, following relativisation of soil variables to standard deviates, was conducted using the asymptotic approximation in Sokal and Rolfe (1995) for samples greater than 40.

2.3. Results

2.3.1. Comparison of turlough soil nutrient properties among two contrasting catchment types

Variations of soil nutrient properties between catchments, among turloughs within catchments and within turloughs were examined. Samples from Lough Cuil Reasc turlough were left out of the analysis as only two samples remained after sample loss (one from the upper zone and one from the lower zone). One sample from each elevational zone was insufficient to provide any information on the degree of variability within that area. $CaCO_3$ was not included in the analysis as transformation did not yield even an approximately normal distribution. An ANOVA summary of variation between catchments is presented in Table 2.4 and summary statistics of the soil physico-chemical properties within each catchment are presented in Table 2.5.

Mean values for each soil property within the upper, middle and lower areas of each catchment are presented in Figure s 2.4 to 2.14. Mean values for each soil property within the upper, middle and lower areas of each turlough within each catchment are presented in Figure s 2.15 to 2.25. An ANOVA summary of variation among turloughs within Coole-Garryland is presented in Table 2.6 and accompanying Bonferroni posthoc comparisons are presented in Table 2.7. Summary statistics of the soil physico-chemical properties of turloughs located within Coole-Garryland are presented in Table 2.8. An ANOVA summary of variation among turloughs within East Burren is presented in Table 2.9 and accompanying Bonferroni posthoc comparisons are presented in Table 2.10. Summary statistics of the soil physico-chemical properties of turloughs located within East Burren are presented in Table 2.11. Results of the two samples from Lough Cuil Reasc are included in the Figure s in order to assess whether they are consistent with samples taken from other turloughs within the East Burren.

2.3.1.1. OM and Inorganic content

OM varied significantly ($p \leq 0.001$, log transformed data, Table 2.4) among catchments with East Burren soils having a higher mean OM content than Coole Garryland soils (Table 2.5). A significant interaction between catchment and sampling location was not detected ($p > 0.05$, Table 2.4), and mean OM content was higher in the East Burren than in Coole-Garryland at each sampling location (upper, middle, lower) (Figure 2.4). Within both catchments the general trend in organic matter variation along the flooding gradient suggests that highest OM contents occur in the lower turlough areas, but the general increasing trend in OM content along the flooding gradient was more pronounced in the East Burren complex than in Coole-Garryland (Figure 2.4). OM also varied highly significantly among turloughs ($p \leq 0.001$, Table 2.4).

Within Coole-Garryland, OM varied highly significantly among turloughs ($p \leq 0.001$, log transformed data, Table 2.6). However Hawkhill turlough that had significantly higher mean OM content (Table 2.8) than Coole ($p \leq 0.01$), Garryland ($p \leq 0.01$) or Caherglassaun ($p \leq 0.05$, Bonferroni post hoc comparisons, Table 2.7). There was no significant difference between any of the other three turloughs ($p > 0.05$, Table 2.7). A significant interaction between turlough and location was not detected ($p > 0.05$, Table 2.6) indicating that Hawkhill had higher mean OM content than the other three turloughs within this catchment at all three sampling locations (Figure 2.15). OM also varied with weak significance ($p < 0.05$, log transformed data, Table 2.9) among the East Burren turloughs, where Knockaunroe had significantly lower mean OM content than Cooloorta ($p < 0.05$, Table 2.10) and Gortlecka ($p < 0.05$, Table 2.10). There was no significant difference between Gortlecka and Cooloorta ($p > 0.05$, Table 2.10).

Figure 2.15 suggests that different trends in OM variation along the flooding gradient occur within each turlough within the East Burren however a significant interaction between turlough and sampling location was not detected ($p > 0.05$, Table 2.9) most likely due to the high degree of variation within Cooloorta and Knockaunroe. OM contents within the upper and lower areas within Lough Cuil Reasc are within the range of values recorded at the same locations within the other three East Burren turloughs. Mean values have been presented in Table 2.11 but data from Lough Cuil Reasc were not included in the statistical analyses.

Inorganic content also varied significantly ($p \leq 0.01$, log transformed data, Table 2.4) among catchments with Coole-Garryland soils having a higher mean inorganic content than East Burren soils (Table 2.5). A significant interaction between catchment and sampling location was not detected ($p > 0.05$, Table 2.4), and mean inorganic content was higher in Coole-Garryland than in East Burren at each sampling location (upper, middle, lower) (Figure 2.4b). Inorganic content also varied highly significantly among turloughs ($p \leq 0.001$, Table 2.4). Within Coole-Garryland, inorganic content varied highly significantly among turloughs ($p \leq 0.001$, log transformed data, Table 2.6), however, it was only Hawkhill turlough that had significantly lower mean inorganic content (Table 2.8) than Coole ($p \leq 0.01$), Garryland ($p \leq 0.01$) or Caherglassaun ($p \leq 0.05$, Bonferroni post hoc comparisons, Table 2.7). There was no significant difference between any of the other three turloughs ($p > 0.05$, Table 2.7). A significant interaction between turlough and location was not detected ($p > 0.05$, Table 2.6) indicating that Hawkhill had lower mean inorganic content than the other three turloughs within this catchment at all three sampling locations (Figure 2.15b). Inorganic content also varied with weak significance ($p < 0.05$, log transformed data, Table 2.9) among the East Burren turloughs, where Knockaunroe had significantly lower mean inorganic content than Cooloorta ($p < 0.05$, Table 2.10) and Gortlecka ($p < 0.05$, Table 2.10). There was no significant difference between Gortlecka and Cooloorta ($p > 0.05$, Table 2.10).

Figure 2.15b suggests that different trends in inorganic content variation along the flooding gradient occurred within each turlough within the East Burren. However a significant interaction between turlough and sampling location was not detected ($p > 0.05$, Table 2.9) most likely due to the high degree of variation within Cooloorta and Knockaunroe. Inorganic contents within the upper and lower areas within Lough Cuil Reasc are within the range of values recorded at the same locations within the other three East Burren turloughs (Table 2.11)

2.3.1.2 pH, Ca_t, $CaCO_3$

pH varied significantly ($p \leq 0.001$, Table 2.4) among catchments with East Burren soils having a higher mean pH (more alkaline) than Coole Garryland soils (Table 2.5). A significant interaction between catchment and sampling location was detected ($p \leq 0.001$, Table 2.4) suggesting that the catchment difference in pH is to some extent dependent on whether samples are collected from the upper, middle or lower zones. Figure 2.5 suggests that pH variation with location along the flooding gradient differs subtly amongst the two catchments and that variation among catchments is less pronounced within the lower zones. An increasing trend in pH from upper to lower areas occurs within Coole Garryland catchment whereas highest mean pH is associated with the middle areas in the East Burren catchment. pH also varied highly significantly among turloughs ($p \leq 0.001$, Table 2.4). Within Coole-Garryland, pH varied highly significantly among turloughs ($p \leq 0.001$, Table 2.6). However Hawkhill turlough that had significantly higher mean pH (Table 2.8) than Coole ($p \leq 0.001$), Garryland ($p \leq 0.001$) or Caherglassaun ($p \leq 0.001$, Bonferroni post hoc comparisons, Table 2.7). There was no significant difference between any of the other three turloughs ($p > 0.05$, Table 2.7). A significant interaction between turlough and sampling location was detected ($p \leq 0.05$, Table 2.6) indicating that the higher pH values associated with soils from Hawkhill are dependent on sampling location (Figure 2.16) with greater degrees of variation associated with the lower zones of Caherglassaun, Garryland and Coole in comparison to the upper and middle zones of these turloughs. pH also varied significantly ($p \leq 0.001$, Table 2.9) among the East Burren turloughs, where Knockaunroe had significantly higher mean pH than Cooloorta ($p \leq 0.001$, Table 2.10) and Gortlecka ($p \leq 0.001$, Table 2.10). There was no significant difference between Gortlecka and Cooloorta ($p > 0.05$, Table 2.10). A significant interaction between turlough and sampling location was not detected ($p > 0.05$, Table 2.9) indicating that Knockaunroe has higher pH than Gortlecka and Cooloorta at each sampling location (Figure 2.16). pH values within the upper and lower areas within Lough Cuil Reasc were within the range of values recorded at the same locations within the other three East Burren turloughs.

Ca_t varied significantly ($p \leq 0.01$, log transformed data, Table 2.4) among catchments with East Burren soils having a higher mean Ca_t content than Coole Garryland soils (Table 2.5). A weak but significant interaction between catchment and sampling location was detected ($p \leq 0.05$, Table 2.4) indicating that the variation amongst catchments is dependent to some extent on sampling location. Figure 2.7 illustrates that differing trends in Ca_t variation along the flooding gradient occurred within turloughs associated with the contrasting catchments. Similar concentrations of Ca_t occurred in the upper, middle and lower zones of Coole Garryland. In contrast, elevated concentrations of Ca_t and a high degree of variation were associated with the middle zones along the flooding gradient within the East Burren. Ca_t also varied highly significantly among turloughs ($p \leq 0.001$, Table 2.4).

Within Coole Garryland, Ca_t varied with weak significance among turloughs ($p \leq 0.05$, log transformed data, Table 2.6), however Bonferroni post hoc comparisons did not reveal significant differences between any of the turloughs in this catchment ($p > 0.05$, Table 2.7) most likely due to the high degree of variation in Ca_t concentrations within Hawkhill, Caherglassaun and Coole (Table 2.8, Figure 2.18). Figure 2.18 indicates that trends in Ca_t variation along the flooding gradient differed among turloughs in Coole Garryland however a significant interaction effect was not detected between turlough and sampling location, most likely due to the high degree of variation in the lower turlough areas, particularly in Hawkhill, Caherglassaun and Coole. Ca_t varied highly significantly ($p \leq 0.001$, log transformed data, Table 2.9) among turloughs located within the East Burren, where Knockaunroe had significantly higher mean Ca_t than Gortlecka ($p \leq 0.001$, Table 2.10) or Cooloorta ($p \leq 0.001$, Table 2.10). There was no significant difference between Gortlecka and Cooloorta ($p > 0.05$, Table 2.10). A significant interaction effect was detected between turlough and sampling location ($p \leq 0.05$, Table 2.9) and it is clear from Figure 2.18 that Ca_t concentrations exhibited an extremely high degree of variation within the East Burren turloughs. Mean Ca_t concentrations were higher in Knockaunroe than Cooloorta and Gortlecka within all sampling locations (Figure 2.18) however very different trends in Ca_t variation along the flooding gradient occurred within Cooloorta and Gortlecka (Figure 2.18). Ca_t values within the upper and lower areas within Lough Cuil Reasc were within the range of values recorded at the same locations within Cooloorta and Gortlecka. Trends in $CaCO_3$ variation within and among both catchments closely mirrored those associated with Ca_t. Figure 2.6 illustrates that differing trends in $CaCO_3$ variation along the flooding gradient occurred within turloughs associated with the contrasting catchments. Similar concentrations of $CaCO_3$ occurred in the upper, middle and lower zones of Coole Garryland. In contrast, elevated concentrations of $CaCO_3$ and a high degree of variation were associated with the middle zones along the flooding gradient within the East Burren. Figure 2.17 indicates that trends in $CaCO_3$ variation along the flooding gradient differed among turloughs in Coole Garryland, with marginally higher $CaCO_3$ concentrations and higher degrees of variation associated with the lower areas of Hawkhill and Garryland in comparison to the upper and middle areas. A similar trend was not associated with Caherglassaun or Coole.

There was a high degree of variation in the lower turlough areas, particularly in Hawkhill, Caherglassaun and Coole. Figure 2.17 illustrates that that $CaCO_3$ concentrations exhibited an extremely high degree of variation within the East Burren turloughs. Mean $CaCO_3$ concentrations were higher in Knockaunroe than Cooloorta and Gortlecka within all sampling locations (Figure 2.17) however very different trends in $CaCO_3$ variation along the flooding gradient occurred within Cooloorta and Gortlecka (Figure 2.17). $CaCO_3$ values within the upper and lower areas within Lough Cuil Reasc were within the range of values recorded at the same locations within Cooloorta and Gortlecka.

2.3.1.3 N_t

Mean N_t concentrations varied significantly ($p \leq 0.01$, Table 2.4) among catchments with East Burren soils having a higher mean N_t content than Coole Garryland soils (Table 2.5). A significant interaction between catchment and sampling location was not detected ($p > 0.05$, Table 2.4) indicating that variation of N_t among catchments is independent of sampling location (Figure 2.8). Mean N_t concentrations also varied highly significantly among turloughs ($p \leq 0.001$, Table 2.4). Within Coole Garryland, N_t varied highly significantly among turloughs ($p \leq 0.001$, Table 2.6), where Garryland and Hawkhill had significantly higher N_t concentrations than Caherglassaun ($p \leq 0.001$, Table 2.7) and Coole ($p \leq 0.001$, Table 2.7). There was no significant difference between Coole and Caherglassaun ($p > 0.05$, Table 2.7) and Hawkhill and Garryland ($p > 0.05$, Table 2.7). A significant interaction between turlough and sampling location was not detected indicating that significant variations among turloughs within this catchment are independent of location. Mean N_t concentrations also varied significantly ($p \leq 0.001$, Table 2.9) among turloughs in the East Burren where Gortlecka had significantly higher (Table 2.11) N_t concentrations than Knockaunroe ($p \leq 0.001$, Table 2.10) and Cooloorta ($p \leq 0.001$, Table 2.10). There was no significant difference in mean N_t concentations between Knockaunroe and Cooloorta. A significant interaction between turlough and location was detected ($p < 0.05$, Table 2.9) indicating that the significantly higher concentrations associated with Gortlecka are dependent on sampling location (Figure 2.19). N_t values within the upper and lower areas within Lough Cuil Reasc were within the range of values recorded in the other three turloughs in the East Burren.

2.3.1.4 P_t, P_{feo}, P_m

P_t varied significantly ($p \leq 0.001$, Table 2.4) among catchments with Coole Garryland soils having a higher mean P_t content than East Burren soils (Table 2.5). A significant interaction between catchment and sampling location was not detected ($p > 0.05$, Table 2.4), and mean P_t content was higher in Coole Garryland than East Burren at each sampling location (Figure 2.9). Within both catchments there was a general increasing trend in mean P_t concentrations along the flooding gradient but a greater degree of variation is associated with the East Burren turloughs (Figure 2.9).

P_t also varied highly significantly among turloughs ($p \leq 0.001$, Table 2.4). Within Coole Garryland, however, there was no significant difference in mean P_t concentrations among turloughs ($p > 0.05$, Table 2.6). A significant interaction between turlough and sampling location was not detected ($p > 0.05$, Table 2.6) indicating that similar mean P_t concentrations occur within the upper, middle and lower areas of the Coole Garryland turloughs (Figure 2.20). Figure 2.20 indicates that a high degree of variation was associated with the lower areas of Hawkhill, Caherglassaun, Garryland and Coole.

P_t varied highly significantly among East Burren turloughs, with Gortlecka having significantly higher mean P_t concentrations than Knockaunroe ($p \leq 0.001$, Table 2.10) and Cooloorta ($p \leq 0.001$, Table 2.10). There was no significant difference between Knockaunroe and Cooloorta ($p > 0.05$, Table 2.10). A significant interaction was detected between turlough and location ($p \leq 0.001$, Table 2.9). Contrasting trends in P_t variation were associated with the three East Burren turloughs. Similar trends in P_t variation occurred along the flooding gradients within Knockaunroe and Cooloorta which are in contrast to the trend which occurred in Gortlecka, within which maximum mean P_t concentrations were associated with the lower turlough area (Figure 2.20). P_t values within the upper and lower areas within Lough Cuil Reasc were within the range of values recorded within Knockaunroe and Cooloorta.

A significant difference in mean P_{feo} soil concentrations was not detected ($p > 0.05$, log transformed data, Table 2.4) even though mean P_{feo} concentrations were higher in the Coole Garryland complex than in the East Burren complex (Table 2.5). A significant interaction effect was not detected ($p > 0.05$, Table 2.4) between catchment and location and Figure 2.10 indicates that each location along the flooding gradient was characterised by a high degree of variation, particularly in the East Burren, most likely preventing the detection of a significant difference among catchments. P_{feo} was found to vary significantly among turloughs ($p \leq 0.01$, Table 2.4). Within Coole Garryland however P_{feo} did not vary significantly among turloughs and there was also a lack of a significant interaction effect between turlough and location ($p > 0.05$, Table 2.6) within this catchment. Within the East Burren however, P_{feo} varied highly significantly among turloughs ($p \leq 0.001$, Table 2.9), with Gortlecka having significantly higher mean P_{feo} concentrations (Table 2.11) than Knockaunroe ($p \leq 0.001$, Table 2.10) and Cooloorta ($p \leq 0.001$, Table 2.10), and Knockaunroe had higher concentrations than Cooloorta ($p \leq 0.01$, Table 2.10). These significant differences are dependent on sampling location. However as a highly significant ($p \leq 0.001$) interaction effect was detected between turlough and location ($p \leq 0.001$, Table 2.9). Figure 2.21 illustrates that contrasting trends in P_{feo} variation occur along the flooding gradient within Knockaunroe, Gortlecka and Cooloorta. P_{feo} values within the upper and lower areas within Lough Cuil Reasc were within the range of values recorded within Knockaunroe and Cooloorta.

P_m varied significantly ($p \leq 0.01$, log transformed data, Table 2.4) among catchments, with East Burren soils having a higher mean P_m content than Coole Garryland soils (Table 2.5). Even though mean P_m concentrations were higher at each location within East Burren than in Coole Garryland (Figure 2.11) the high degree of variation associated with the upper and lower areas of the East Burren resulted in a weakly significant ($p \leq 0.05$, Table 2.4) interaction effect being detected between catchment and location. P_m also varied highly significantly ($p \leq 0.001$, Table 2.4) among turloughs.

P_m varied highly significantly ($p \leq 0.001$, Table 2.6) among turloughs in the Coole Garryland catchment however it was only Hawkhill turlough that had significantly higher mean P_m content (Table 2.8) than Caherglassaun ($p \leq 0.05$, Table 2.7), Coole ($p \leq 0.001$, Table 2.7) and Garryland ($p \leq 0.05$, Table 2.7, Bonferroni post hoc comparisons). A significant interaction effect ($p \leq 0.01$, Table 2.6) was detected between turlough and location within Coole Garryland. Figure 2.22 illustrates the fact that the higher mean P_m concentrations associated with Hawkhill were dependent on sampling location, as highest mean P_m concentrations occurred in Caherglassaun in the upper areas and Garryland in the lower areas. P_m also varied highly significantly ($p \leq 0.001$, log transformed data, Table 2.9) among turloughs located in the East Burren catchment, where Gortlecka had significantly higher P_m content than Cooloorta ($p \leq 0.001$, Table 2.10) and Knockaunroe had significantly higher mean P_m content than Cooloorta ($p \leq 0.01$, Table 2.10). These significant differences must be considered with caution however due to the significant interaction effect between turlough and location ($p \leq 0.05$, Table 2.9) within this catchment and the high degree of variation in the data set, particularly within Gortlecka and Cooloorta (Figure 2.22). P_m values within the upper and lower areas within Lough Cuil Reasc were within the range of values recorded Knockaunroe and Cooloorta.

2.3.1.5 K_t, Mg_t, Fe_t

K_t varied highly significantly ($p \leq 0.001$, log transformed data, Table 2.4) among catchments, with Coole Garryland soils having a higher mean K_t content than East Burren soils (Table 2.5). A significant interaction effect between catchment and location was not detected ($p > 0.05$, Table 2.4) and mean K_t content was higher in Coole Garryland at each sampling location along the flooding gradient (Table 2.5, Figure 2.12). K_t also varied significantly among turloughs ($p \leq 0.001$, Table 2.4). Within Coole Garryland, K_t varied highly significantly ($p \leq 0.001$, Table 2.6) among turloughs, where Coole had significantly higher mean K_t content than Caherglassaun ($p \leq 0.01$, Table 2.7) and Hawkhill ($p \leq 0.001$, Table 2.7) and Garryland had significantly ($p \leq 0.05$, Table 2.7) higher mean K_t content than Hawkhill. A significant interaction effect was not detected between turlough and location ($p > 0.05$, Table 2.6) indicating that these significant differences among turloughs with Coole Garryland are independent of sampling location (Figure 2.4). K_t also varied highly significantly among turloughs in the East Burren catchment ($p \leq 0.001$, Table 2.9) where mean K_t content was higher in Gortlecka than Knockaunroe ($p \leq 0.001$, Table 2.10). There were no significant differences in mean K_t content between Gortlecka and Cooloorta ($p > 0.05$, Table 2.10) and Knockaunroe and Cooloorta ($p > 0.05$, Table 2.10). A significant interaction effect was not detected between turlough and location in the East Burren catchment indicating that the significant differences between Gortlecka and Knockaunroe are independent of the location from which samples were taken along the flooding gradient, also illustrated by Figure 2.23. K_t values from the upper and lower areas within Lough Cuil Reasc were within the range of values recorded Knockaunroe and Cooloorta.

Mg_t varied highly significantly ($p \leq 0.001$, Table 2.4) among catchments, with Coole Garryland soils having a higher mean Mg_t content than East Burren soils. A significant interaction between catchment and location was detected ($p \leq 0.01$, Table 2.4) indicating that the variation in Mg_t content among catchments is influenced by the location from which samples were taken along the flooding gradient (Figure 2.13). Figure 2.13 illustrates that Mg_t concentations were higher within Coole Garryland and East Burren at each sampling location however the difference between catchments was most pronouned in the lower sampling locations. Mg_t did not vary significantly among turloughs ($p \leq 0.001$, Table 2.4). Indeed Mg_t did not vary significantly among turloughs within Coole Garryland ($p > 0.05$, Table 2.6) or the East Burren ($p > 0.05$, Table 2.9). Figure 2.24 illustrates the contrasting trends in Mg_t variation along the flooding gradients within turloughs located with both catchments. High degrees of variation in the dataset most likely prevented the detection of an interaction effect between turlough and location within Coole Garryland.

Fe_t varied highly significantly ($p \leq 0.001$, log transformed data, Table 2.4) among catchments with Coole Garryland having a higher mean Fe_t content than East Burren soils (Table 2.5). A significant interaction between catchment and location along the flooding gradient was not detected and mean Fe_t content was higher in Coole Garryland than in the East Burren at each location along the flooding gradient (Figure 2.14). Fe_t content also varied significantly among turloughs ($p \leq 0.01$, Table 2.4). Within Coole Garryland, Fe_t varied highly significantly among turloughs ($p \leq 0.001$, Table 2.6, log transformed data, Table 2.6) where Hawkhill had significantly lower mean Fe_t content than Caherglassaun ($p \leq 0.05$, Table 2.7), Coole ($p \leq 0.01$, Table 2.7) and Garryland ($p \leq 0.05$, Table 2.7). A significant interaction effect was not detected between turlough and location and the significant differences observed between Hawkhill and the other three turloughs within the catchment were independent of location (Figure 2.25). Within the East Burren, mean Fe_t concentrations did not vary significantly among turloughs (Table 2.9) and the lack of a significant interaction effect between turlough and location within this catchment indicates that similar mean Fe_t concentrations were associated with the upper, middle and lower areas within each turlough, which is illustrated by Figure 2.25.

Table 2.4: Analysis of variance summary of soil property variation between catchments and among turloughs with interaction effects for sampling location. Symbols: ns = $p > 0.05$; * = $p \leq 0.05$; **= $p \leq 0.01$; *** = $p \leq 0.001$.

	Source of variation							
	Catchment		Turlough		Location		Catchment*Location	
Soil property	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
OM	$74.89_{1,58}$	***	$6.64_{5,7}$	***	$3.79_{2,3}$	*	$0.50_{2,6}$	ns
Inorg	$82.76_{1,58}$	***	$7.13_{5,7}$	***	$5.12_{2,3}$	*	$0.30_{2,6}$	ns
pH	$191.22_{1,58}$	***	$26.14_{5,7}$	***	$10.36_{2,3}$	***	$9.76_{2,6}$	***
Ca_t	$8.67_{1,58}$	**	$14.19_{5,7}$	***	$0.37_{2,3}$	ns	$3.21_{2,6}$	*
N_t	$7.16_{1,58}$	**	$12.34_{5,7}$	***	$2.39_{2,3}$	ns	$0.95_{2,6}$	ns
P_t	$62.27_{1,58}$	***	$10.31_{5,7}$	***	$4.54_{2,3}$	*	$0.40_{2,6}$	ns
P_{feo}	$1.71_{1,58}$	ns	$5.04_{5,7}$	**	$3.58_{2,3}$	*	$0.06_{2,6}$	ns
P_m	$14.35_{1,58}$	**	$8.41_{5,7}$	***	$0.16_{2,3}$	ns	$4.34_{2,6}$	*
K_t	$307.82_{1,58}$	***	$8.09_{5,7}$	***	$3.06_{2,3}$	ns	$0.45_{2,6}$	ns
Mg_t	$143.38_{1,58}$	***	$0.82_{5,7}$	ns	$2.36_{2,3}$	ns	$8.33_{2,6}$	**
Fe_t	$267.25_{1,58}$	***	$4.02_{5,7}$	**	$8.69_{2,3}$	**	$2.64_{2,6}$	ns

Table 2.5: Mean ± SD of soil physico-chemical characteristics within the Coole-Garryland Complex (n=31) and the East Burren Complex (n=27).

	Coole-Garryland	East Burren
%OM	17.7 ± 4.9	34.6 ± 21.2
%Inorg	74.2 ± 8.4	39.1 ± 22.3
pH	6.7 ± 0.8	7.9± 0.7
%$CaCO_3$	8.2 ± 7.9	26.5± 26.8
Ca_t (mg l^{-1})	9213 ± 10830	52970 ± 75790
N_t (mg l^{-1})	4962 ± 1204	5539 ± 1791
P_t (mg l^{-1})	507 ± 161	304 ± 150
P_{feo} (mg l^{-1})	13.6 ± 7.1	10.9 ± 5.7
P_m (mg l^{-1})	4.5 ± 2.6	12.6 ± 12.7
K_t (mg l^{-1})	5190 ± 2067	715 ± 580
Mg_t (mg l^{-1})	2521 ± 1054	735 ± 366
Fe_t (mg l^{-1})	16100 ± 7323	2981 ± 1871

Table 2.6: Analysis of variance summary of soil property variation among turloughs, with interaction effects for sampling location, located within Coole-Garryland catchment.

	Source of Variation					
	Turlough		Location		Turlough*Location	
Soil property	*F*	p	*F*	p	*F*	p
OM	$9.06_{3,4}$	***	$2.41_{2,3}$	ns	$1.72_{6,12}$	ns
Inorg	$13.23_{3,4}$	***	$3.51_{2,3}$	ns	$2.32_{6,12}$	ns
pH	$22.09_{3,4}$	***	$15.87_{2,3}$	***	$2.70_{6,12}$	*
Ca_t	$3.27_{3,4}$	*	$2.49_{2,3}$	ns	$0.85_{6,12}$	ns
N_t	$21.69_{3,4}$	***	$2.65_{2,3}$	ns	$2.23_{6,12}$	ns
P_t	$1.45_{3,4}$	ns	$2.09_{2,3}$	ns	$0.67_{6,12}$	ns
P_{feo}	$2.32_{3,4}$	ns	$1.97_{2,3}$	ns	$1.03_{6,12}$	ns
P_m	$9.08_{3,4}$	***	$2.34_{2,3}$	ns	$3.99_{6,12}$	**
K_t	$8.71_{3,4}$	***	$4.73_{2,3}$	*	$0.37_{6,12}$	ns
Mg_t	$1.59_{3,4}$	ns	$1.78_{2,3}$	ns	$0.89_{6,12}$	ns
Fe_t	$5.45_{3,4}$	**	$1.87_{2,3}$	ns	$2.08_{6,12}$	ns

Table 2.7: Bonferroni post hoc summary for the soil property variation among turloughs located within Coole-Garryland catchment detected in table 2.6.

Post hoc comparison						
Variable	CE-CG	GD-CG	GD-CE	HH-CG	HH-CE	H-G
OM	ns	ns	ns	**	**	*
Inorg	ns	ns	ns	ns	ns	ns
pH	ns	ns	ns	***	***	***
Ca_t	ns	ns	ns	ns	ns	ns
N_t	ns	**	***	***	***	ns
P_m	ns	ns	ns	*	***	*
K_t	**	ns	ns	ns	***	*
Fe_t	ns	ns	ns	*	**	*

Table 2.8: Mean and SD of soil physico-chemical characteristics within Caherglassaun (n=8), Garryland (n=7), Coole (n=9) and Hawkhill (n=7) located within the Coole-Garryland catchment.

	Caherglassaun	Garryland	Coole	Hawkhill
OM %	14.3±1.4	17.6±3.3	16.8±4.9	23±5.4
Inorg %	80.1±3.2	74.3±6.7	72.7±9.7	69.4±9.8
pH	6.3±0.8	6.4±0.8	6.7±0.7	7.4±0.2
$CaCO_3$ %	5.7±2.3	8.3±4.1	10.7±13.4	7.8±5.5
Ca_t (mg l^{-1})	6451±6300	5039±1121	13380±17830	11180±7334
N_t (mg l^{-1})	4329±789	5257±789	4132±850	6459±809
P_t (mg l^{-1})	478±110	484±183	502±218	571±107
P_{feo} (mg l^{-1})	15.4±8.1	15.1±5.9	10.5±7.9	13.9±5.6
P_m (mg l^{-1})	3.9±2.7	4.5±2.4	3.1±1.6	6.8±2.5
K_t (mg l^{-1})	45620±192	5530±1829	6692±1828	3640±1055
Mg_t (mg l^{-1})	2285±1311	2639±692	2923±1277	2158±637
Fe_t (mg l^{-1})	17880±882	16660±8030	18590±8502	10290±3689

Table 2.9: Analysis of variance summary of soil property variation among turloughs, with interaction effects for sampling location, located within East Burren catchment.

	Source of Variation					
	Turlough		Location		Turlough*Location	
Soil property	*F*	p	*F*	p	*F*	p
OM	$4.49_{2,3}$	*	$2.33_{2,3}$	ns	$2.37_{4,9}$	ns
Inorg	$6.14_{2,3}$	*	$3.34_{2,3}$	ns	$3.67_{4,9}$	ns
pH	$38.83_{2,3}$	***	$3.14_{2,3}$	ns	$1.70_{4,9}$	ns
Ca_t	$17.22_{2,3}$	***	$1.59_{2,3}$	ns	$3.31_{4,9}$	*
N_t	$11.55_{2,3}$	***	$1.56_{2,3}$	ns	$3.19_{4,9}$	*
P_t	$51.71_{2,3}$	***	$3.29_{2,3}$	ns	$3.73_{4,9}$	**
P_{feo}	$20.75_{2,3}$	***	$0.83_{2,3}$	ns	$7.12_{4,9}$	***
P_m	$10.64_{2,3}$	***	$3.06_{2,3}$	ns	$2.69_{4,9}$	*
K_t	$8.69_{2,3}$	***	$1.16_{2,3}$	ns	$1.88_{4,9}$	ns
Mg_t	$0.71_{2,3}$	ns	$4.84_{2,3}$	**	$1.64_{4,9}$	ns
Fe_t	$2.55_{2,3}$	ns	$6.34_{2,3}$	**	$1.88_{4,9}$	ns

Table 2.10: Bonferroni post hoc summary for the soil property variation among turloughs located within East Burren catchment detected in table 2.9.

Post hoc comparison			
Variable	GT-CO	KE-CO	KE-GT
OM	ns	*	*
Inorg	ns	*	*
pH	ns	***	***
Ca_t	ns	***	***
N_t	***	ns	***
P_t	***	ns	***
P_{feo}	***	*	***
P_m	***	**	ns
K_t	ns	ns	***

Table 2.11: Mean and SD of soil physico-chemical characteristics within Knockaunroe (n=13), Gortlecka (n=8), Cooloorta (n=6) and Lough Cuil Reasc (n=2) located within the Coole-Garryland catchment.

	Knockaunroe	Gortlecka	Cooloorta	Lough Cuil Reasc
OM %	31.9±25.5	34.4±6.3	40.5±25.4	61.0±28.3
Inorg %	24.4±16.2	53.4±11.8	51.8±26.1	29.0±16.9
pH	8.4±0.5	7.6±0.4	7.2±0.5	7.1±0.1
$CaCO_3$ %	43.7±28.2	12.5±14.6	7.8±6.1	8.8±6.2
Ca_t (mg l^{-1})	94210±89290	17930±37430	10340±14310	14530±14090
N_t (mg l^{-1})	5018±1602	6982±1511	4746±1597	7549±1370
P_t (mg l^{-1})	245±71	484±131	190±66	119±20.5
P_{feo} (mg l^{-1})	9.6±3.7	16.1±6.5	7.3±3.6	10.0±5.4
P_m (mg l^{-1})	9.6±10.1	20.1±14.4	9.3±13.4	31.5±12.7
K_t (mg l^{-1})	415±255	1220±734	690±446	271±195
Mg_t (mg l^{-1})	684±411	805±306	753±378	326±333
Fe_t (mg l^{-1})	2075±1144	2856±836	5111±2545	1236±733

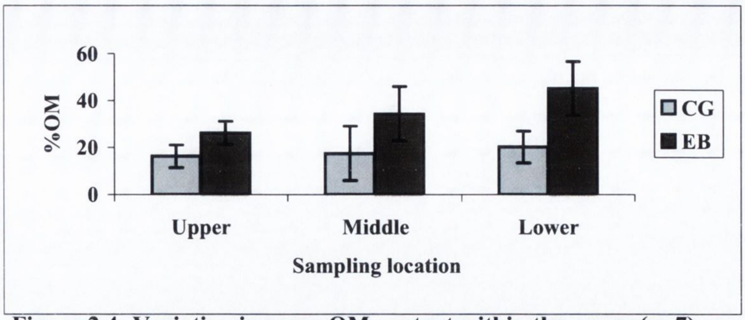

Figure 2.4: Variation in mean OM content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

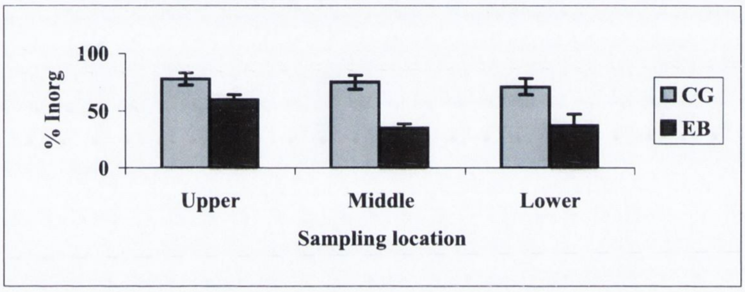

Figure 2.4b: Variation in inorganic (Inorg) content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

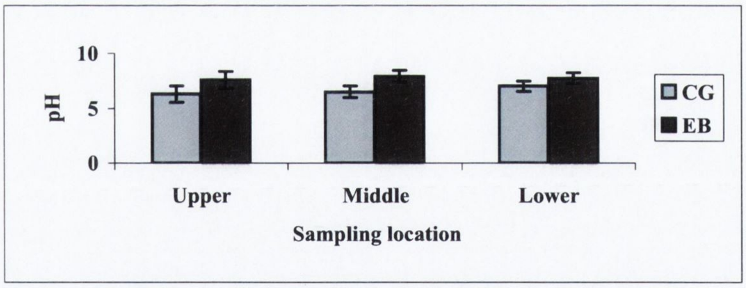

Figure 2.5: Variation in mean pH content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

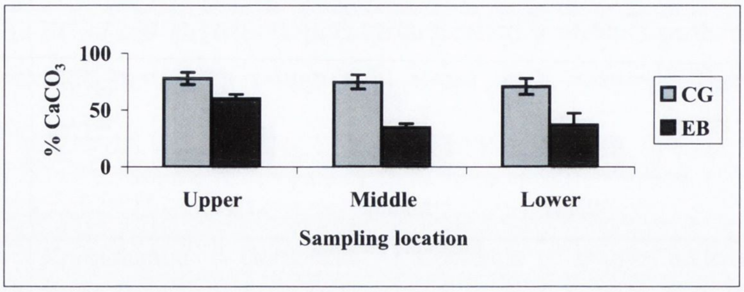

Figure 2.6: Variation in mean $CaCO_3$ content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

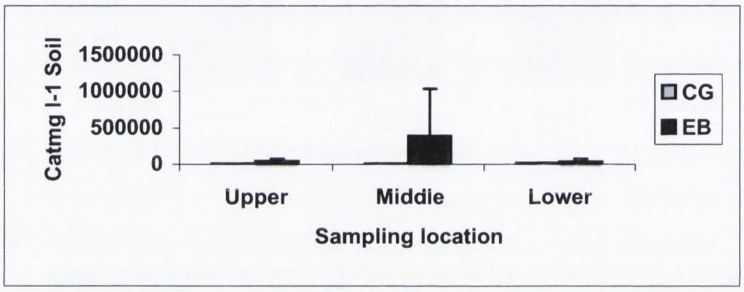

Figure 2.7: Variation in Ca_t content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

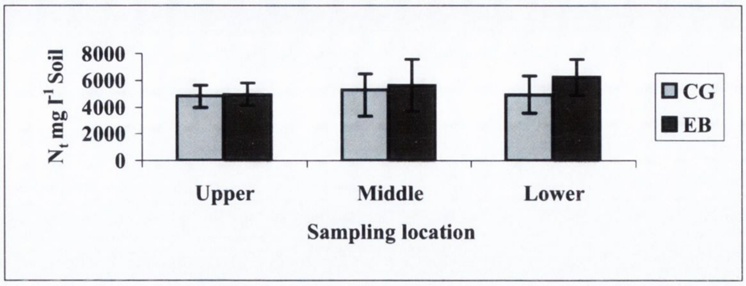

Figure 2.8: Variation in N_t content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

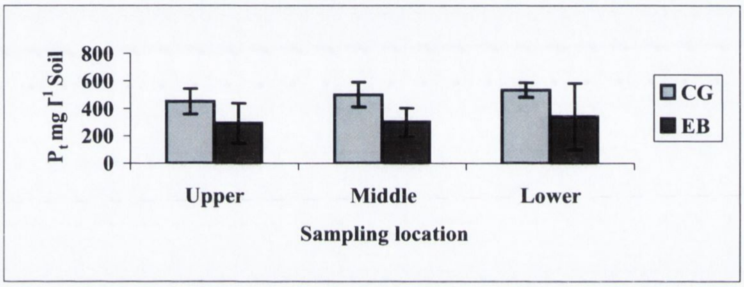

Figure 2.9: Variation in P_t content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

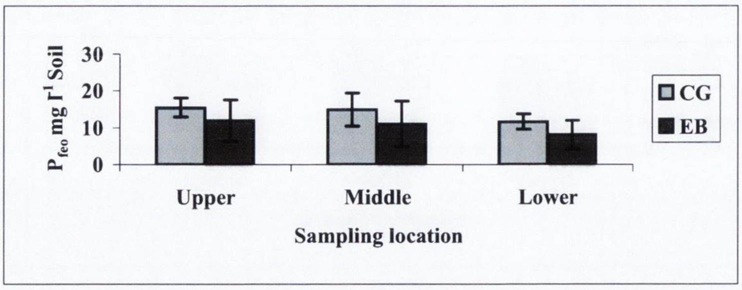

Figure 2.10: Variation in P_{feo} content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

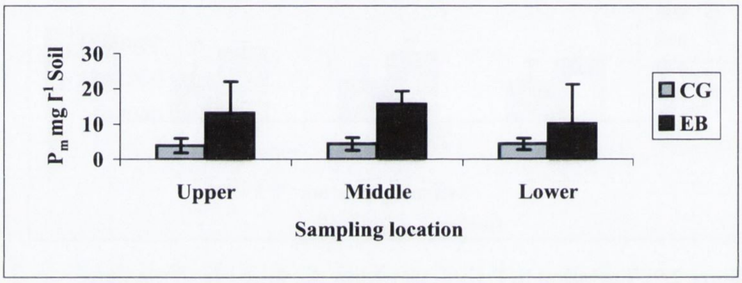

Figure 2.11: Variation in P_m content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

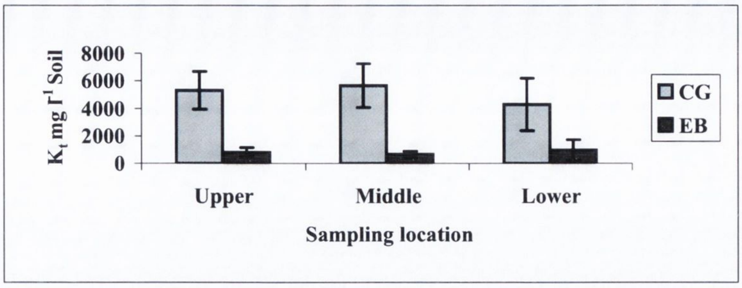

Figure 2.12: Variation in K_t content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

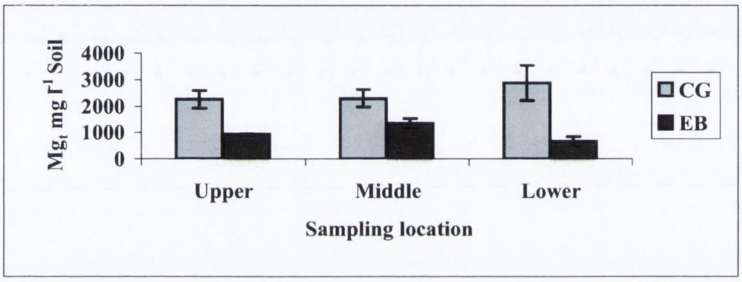

Figure 2.13: Variation in Mg_t content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

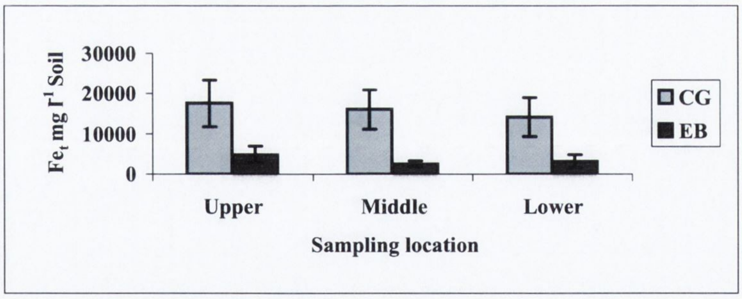

Figure 2.14: Variation in Fe_t content within the upper (n=7), middle (n=7) and lower (n=7) areas of each catchment. CG = Coole Garryland; EB = East Burren. Values are the means and the error bars represent the standard deviation.

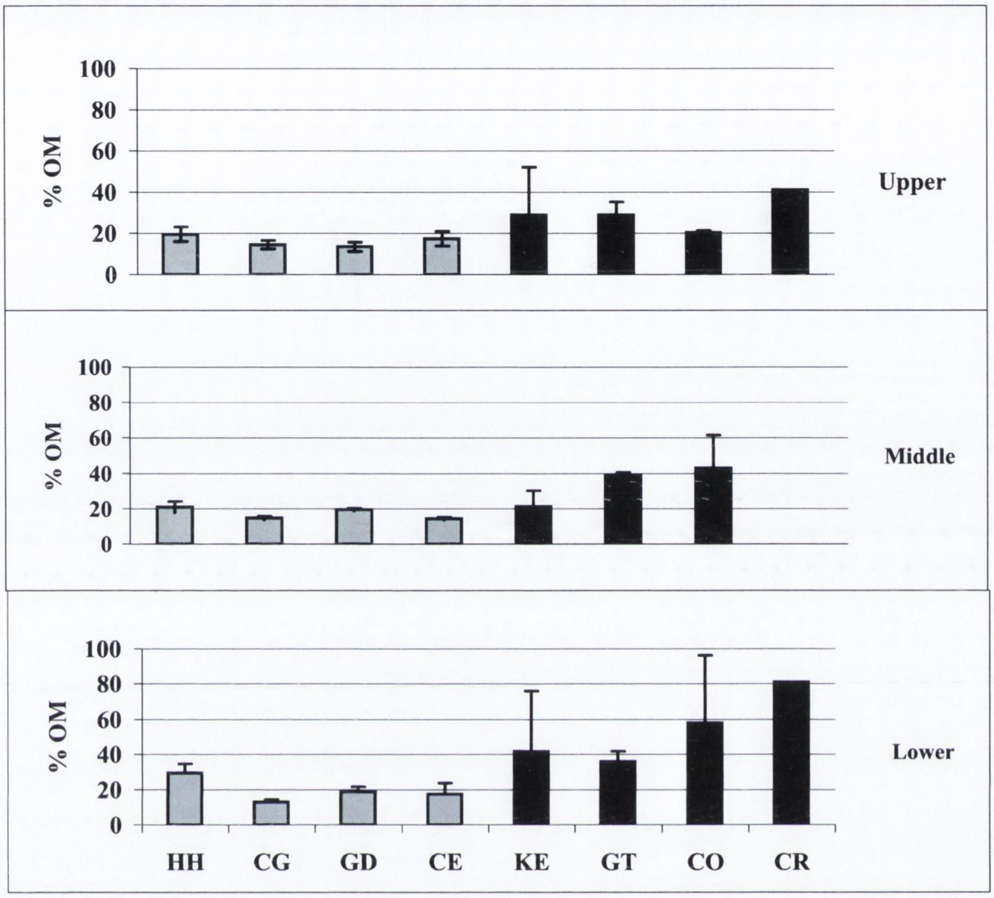

Figure 2.15: Variation in mean OM content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1). Grey bars = Coole Garryland; Black bars = East Burren

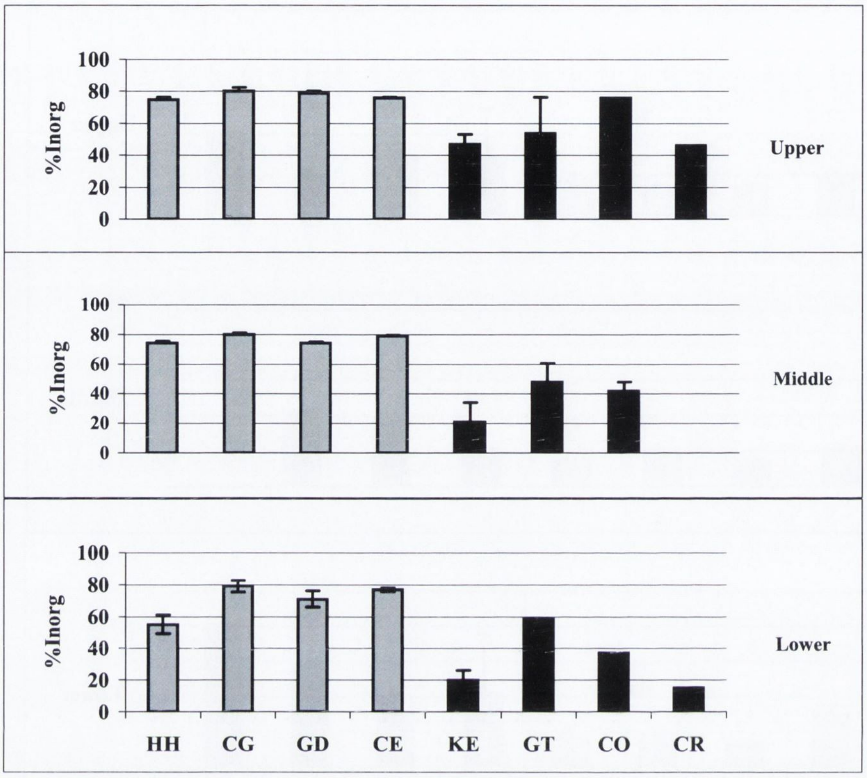

Figure 2.15b: Variation in mean Inorg content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1). Grey bars = Coole Garryland; Black bars = East Burren

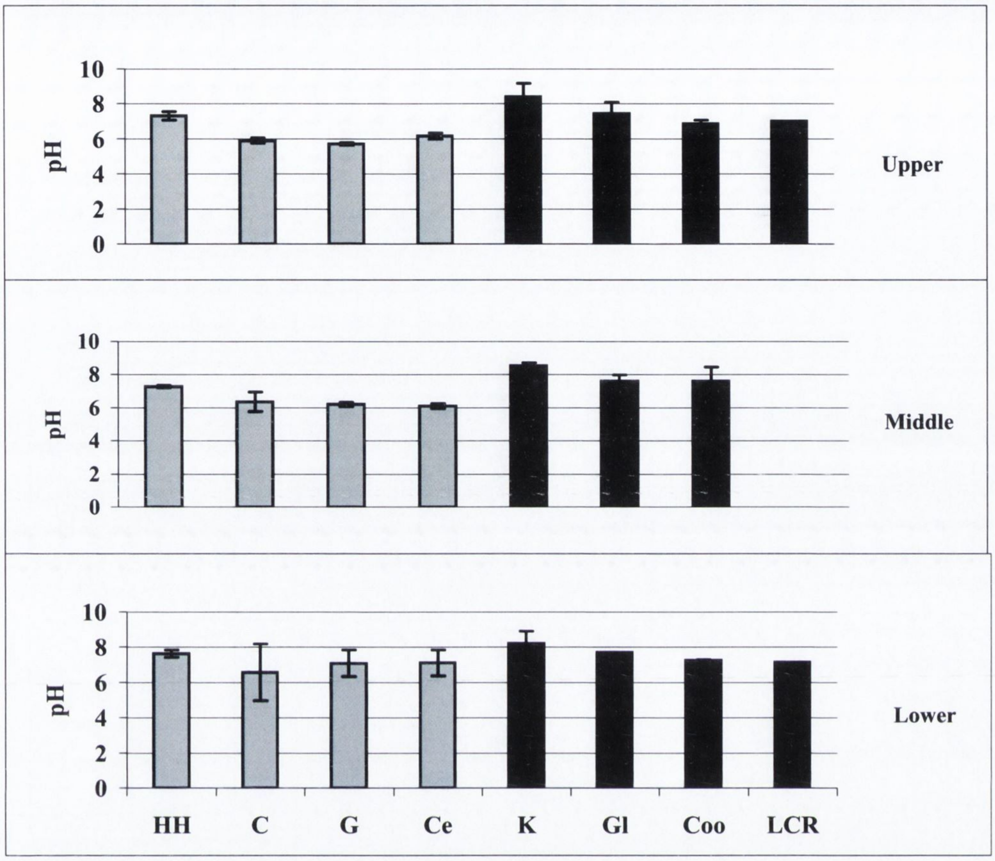

Figure 2.16: Variation in mean pH content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1). Grey bars = Coole Garryland; Black bars = East Burren

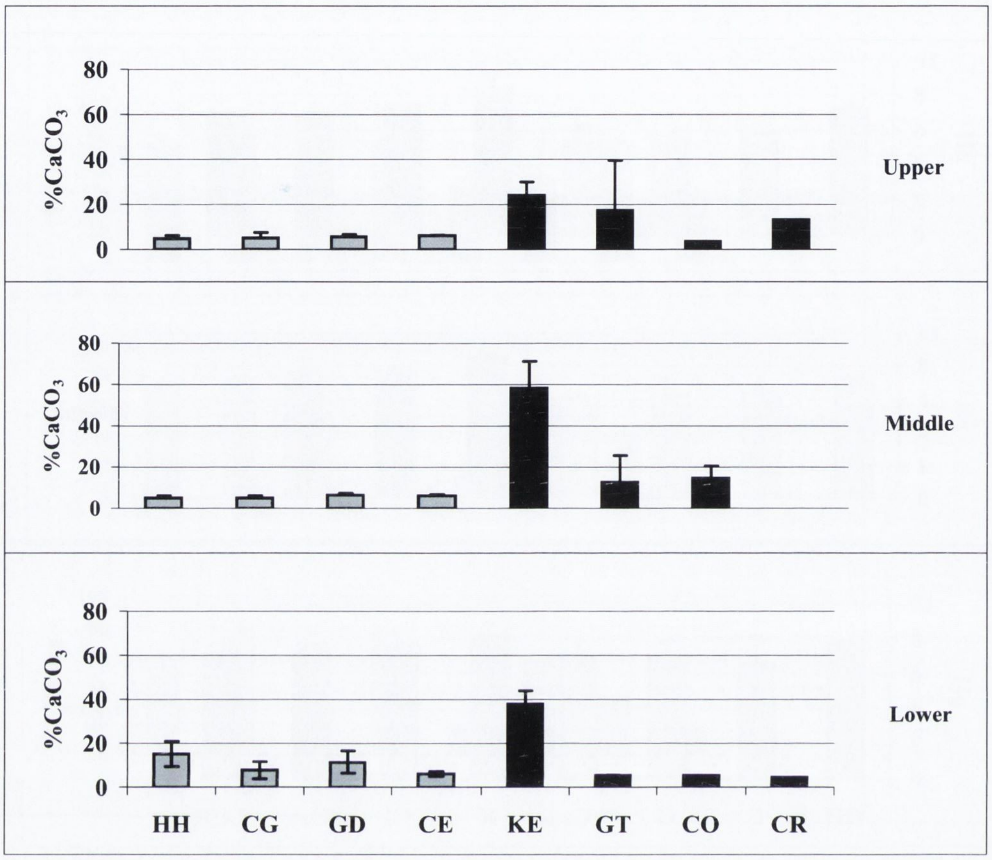

Figure 2.17: Variation in mean $CaCO_3$ content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

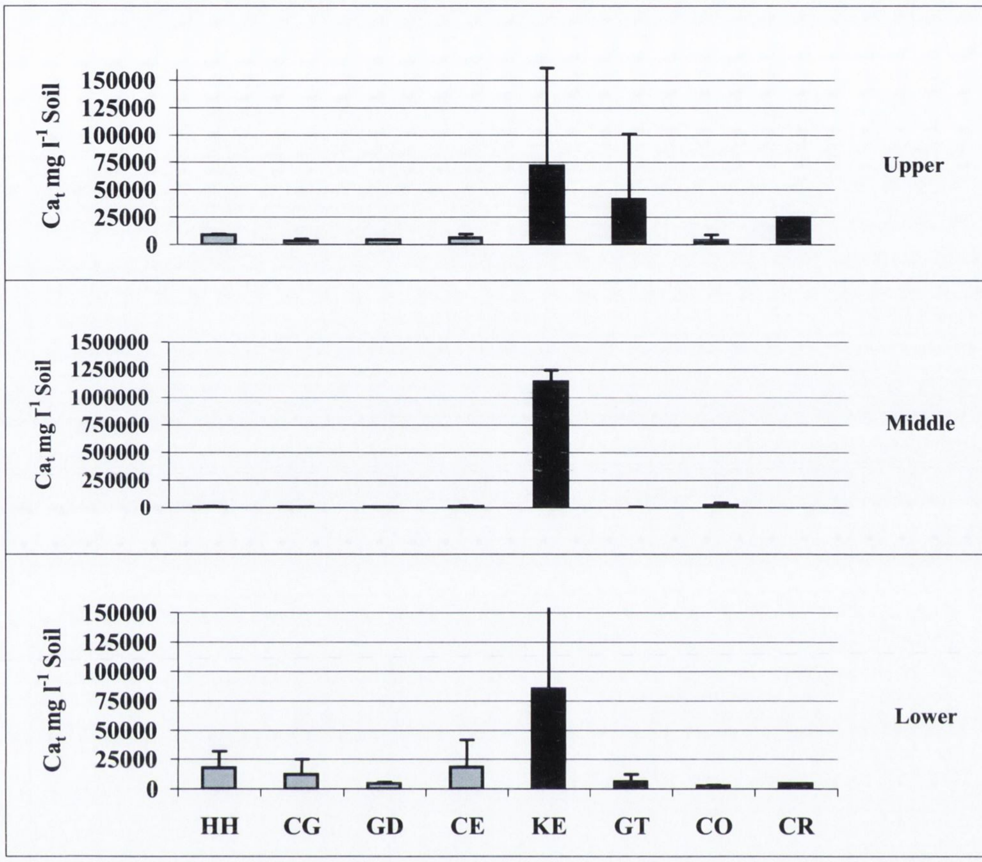

Figure 2.18: Variation in mean Ca_t content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

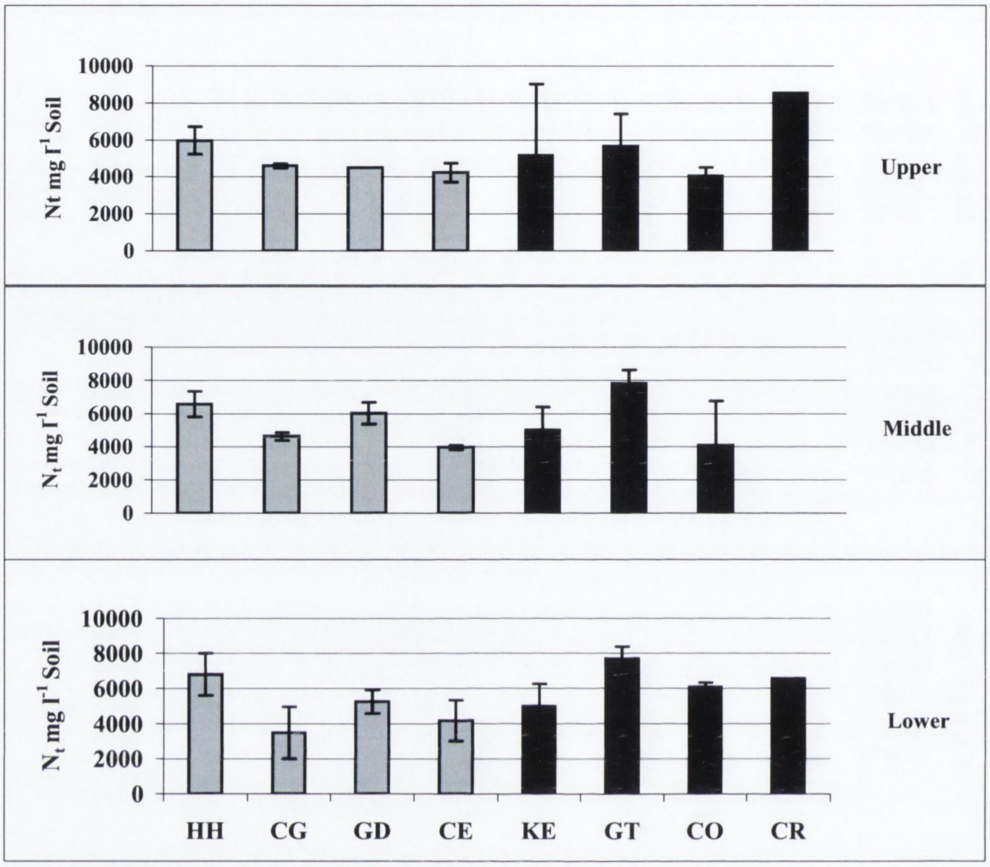

Figure 2.19: Variation in mean N_t content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

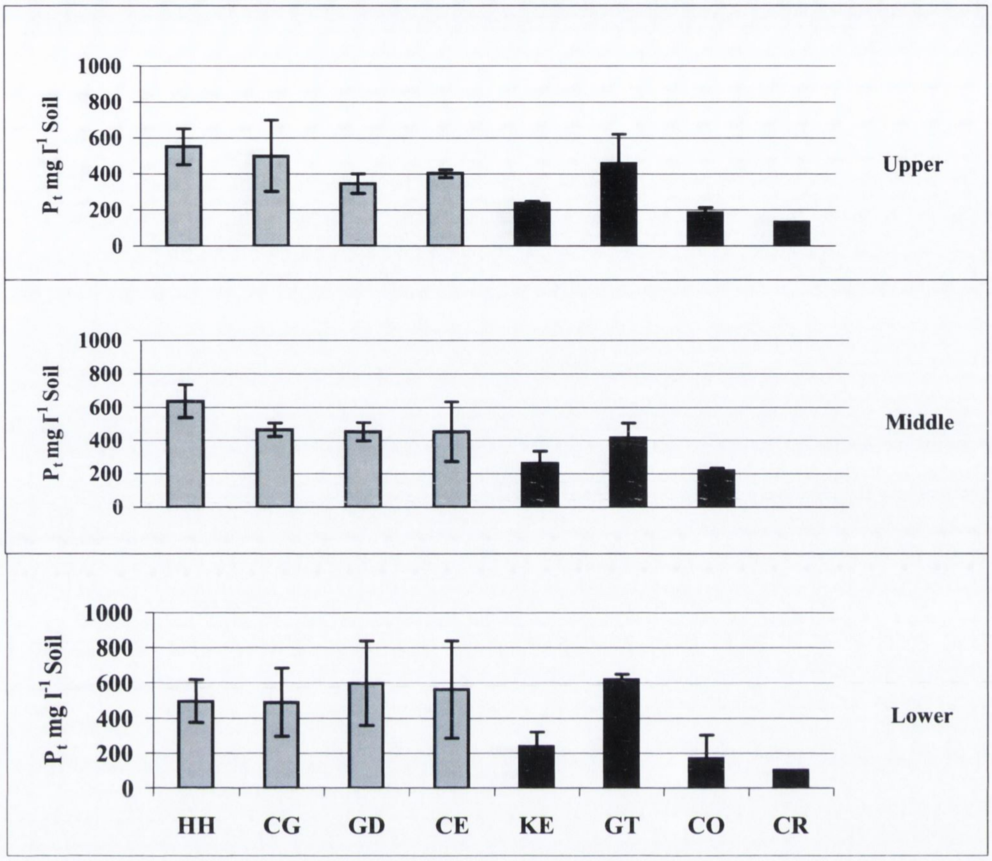

Figure 2.20: Variation in mean P_t content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

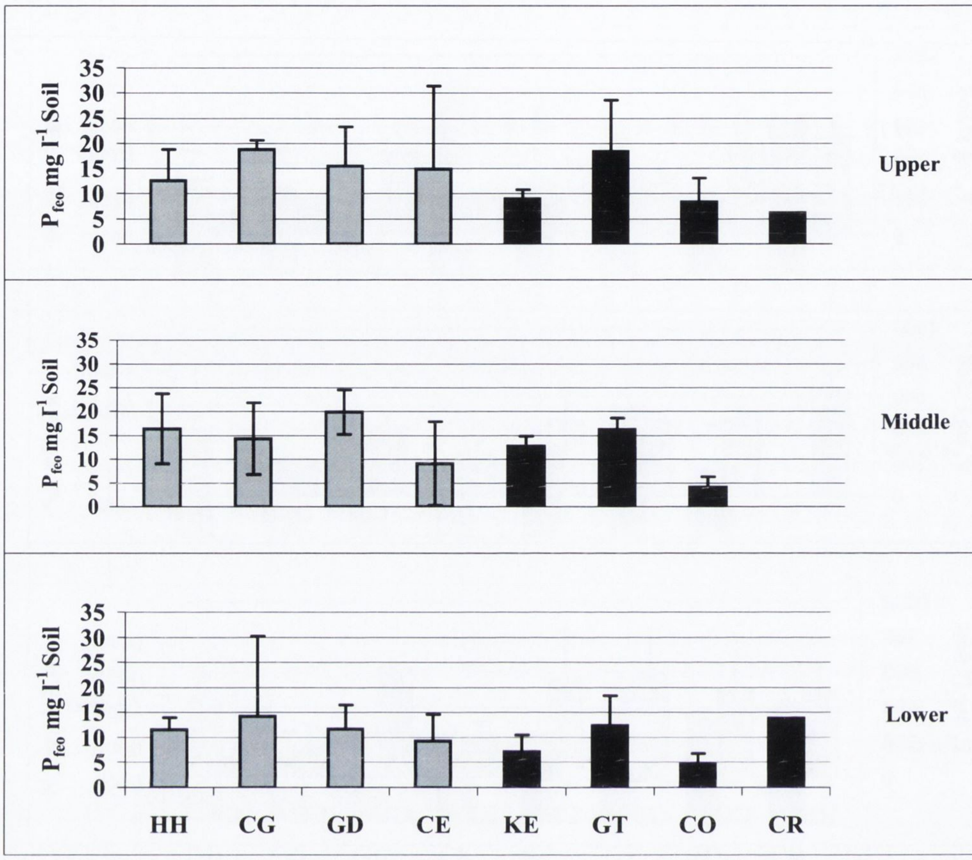

Figure 2.21: Variation in mean P_{feo} content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

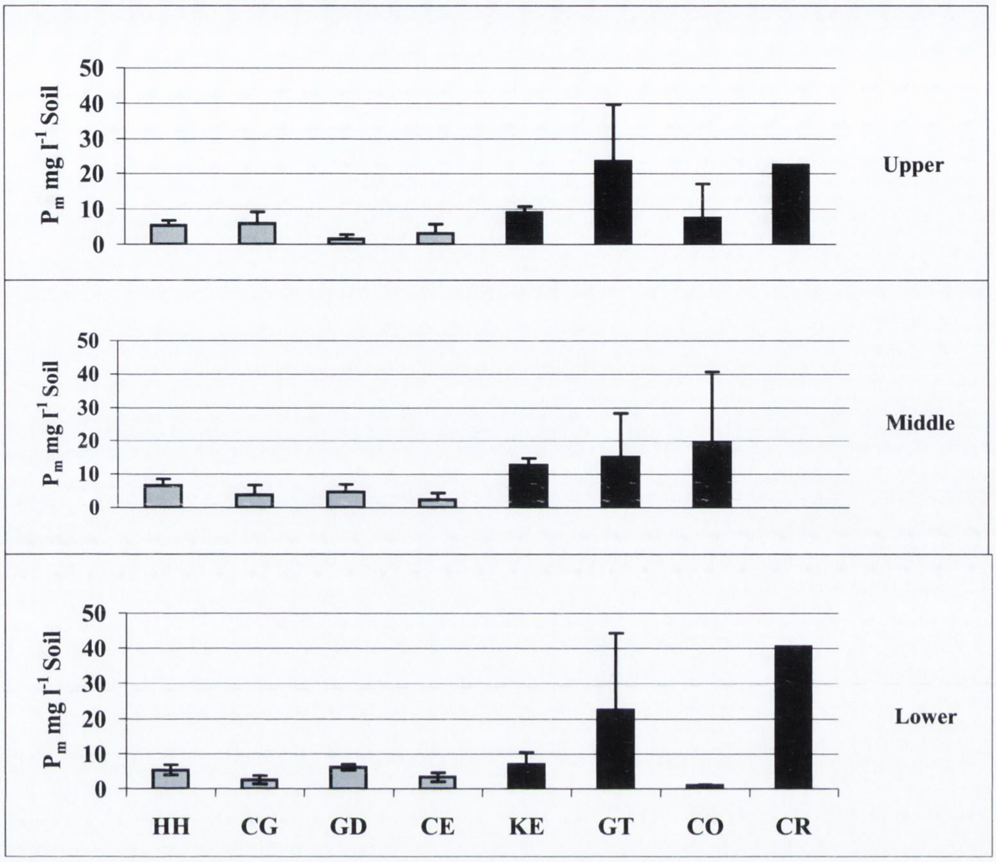

Figure 2.22: Variation in mean P_m content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

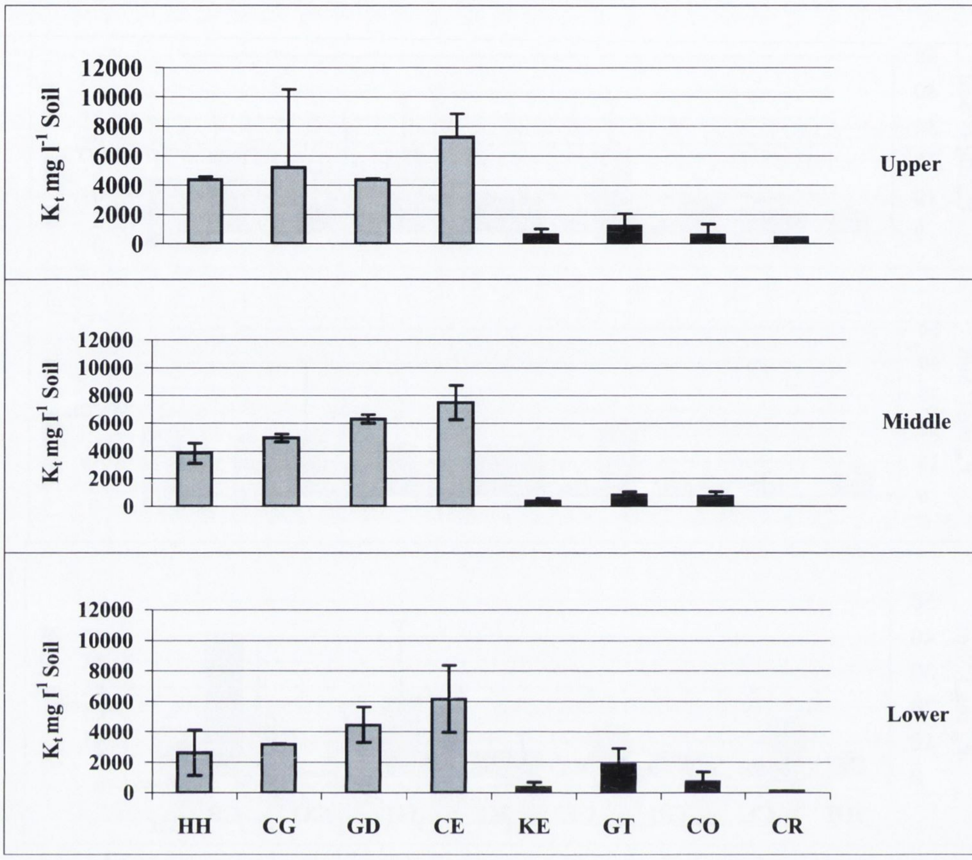

Figure 2.23: Variation in mean K_t content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

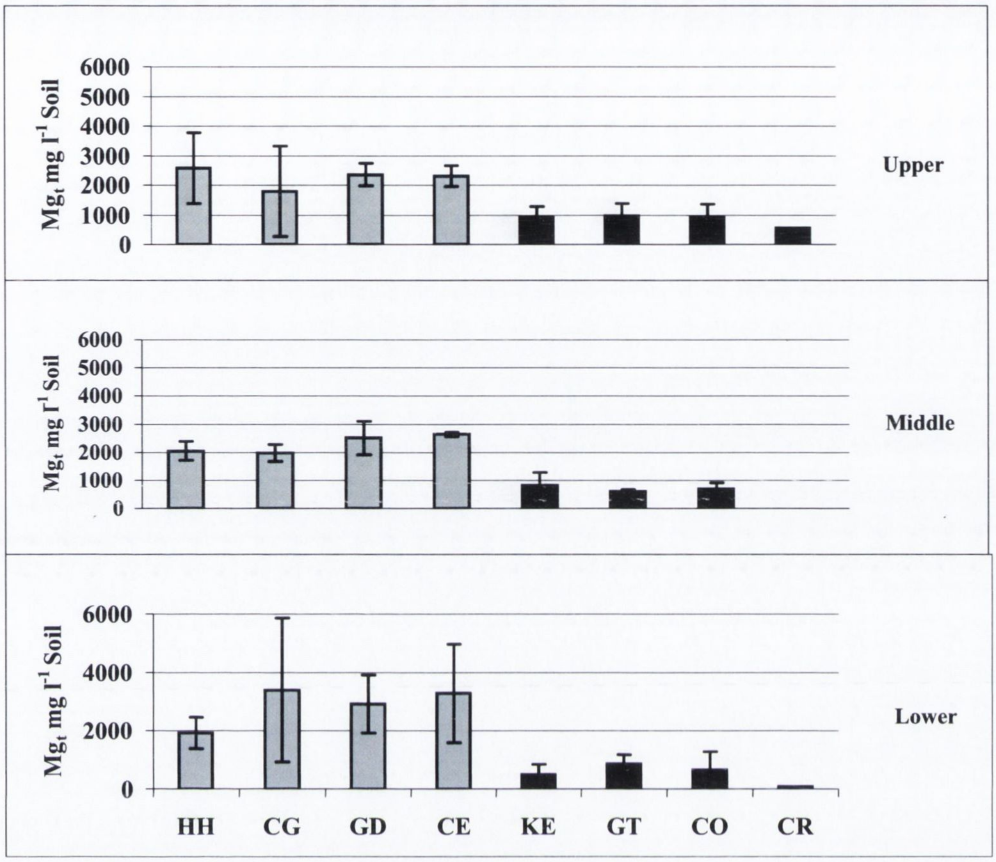

Figure 2.24: Variation in mean Mg_t content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

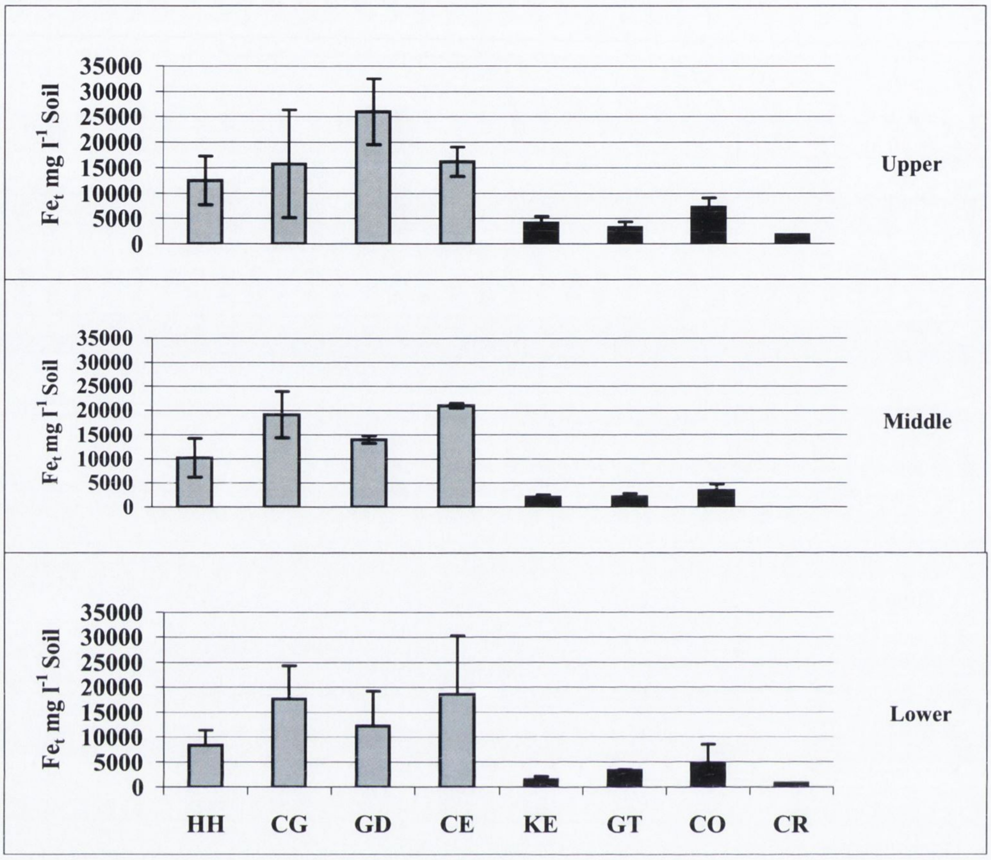

Figure 2.25: Variation in mean Fe_t content along the flooding gradient of each turlough. HH=Hawkhill upper (n=2), middle (n=3) and lower (n=2). CG=Caherglassaun upper (n=2), middle (n=4), and lower (n=2). GD=Garryland upper (n=2), middle (n=2), lower (n=3). CE=Coole upper (n=2), middle (n=2), lower (n=5). KE=Knockaunroe upper (n=2), middle (n=5), lower (n=6). GT=Gortlecka upper (n=3), middle (n=3), lower (n=2). CO=Cooloorta upper (n=2), middle (n=2), lower (n=2). CR=Lough Cuil Reasc upper (n=1), lower (n=1).Grey bars = Coole Garryland; Black bars = East Burren

2.3.2 Variation in nutrient status among common turlough soil types within each catchment.

The soils sampled from each complex were grouped into different soil types based on criteria outlined in Section 2.2.5. The range of soil types sampled within each complex are presented in Table 2.12 with full soil descriptions used for the identification of each soil type presented in Table 2.13-2.20. It is evident from Table 2.12 that seven soil types were sampled from both complexes, including two types of rendzinas, gleys, alluvium, fen peats, peat-marls and marls. Rendzinas were the only soil group common to both complexes from which samples were taken and were associated with upper and middle slopes of turloughs within each catchment (Table 2.13-2.20). The rendzinas within each catchment were distinct from each other in terms of their parent material and it was deemed appropriate to classify these soils to the series level. Gleys occurred in the upper, middle and lower zones of the Coole-Garryland turloughs and the Fen Peats, Peat-marls and Marls were associated with the middle and lower zones of the East Burren turloughs.

Results presented in this section examine variation in nutrient-related properties (pH, $CaCO_3$, OM, Inorg) and N, P and K status among common turlough soil types sampled from each catchment using one-way analysis of variance (Table 2.21) and Bonferroni post-hoc comparisons (Table 2.22). The focus was placed on N, P and K as soil nutrient assessments for conservation assessment purposes would most likely focus on these nutrients as the main plant nutrients and indicators of trophic status. Gleys, Fen Peats, Burren Series Rendzinas and Kilcolgan Series Rendzinas were selected for comparison due to their adequate sample sizes (Table 2.12). Summary statistics of the soil nutrient results for all seven soil types are presented in Table 2.23. Mean pH and $CaCO_3$ content varied highly significantly among the four soil types ($p \leq 0.001$ and $p \leq 0.01$ respectively, Table 2.21). Bonferroni post-hoc comparisons revealed that Burren Series Rendzinas had significantly higher pH than Kilcolgan Series Rendzinas ($p \leq 0.001$, Table 2.22, Figure 2.26a), Gleys ($p \leq 0.001$, Table 2.22, Figure 2.26a) and Fen Peats ($p \leq 0.05$, Table 2.22, Figure 2.26a). The Burren Series Rendzinas also had significantly higher $CaCO_3$ content than the three other soil types also (Table 2.22). A high degree of variation in $CaCO_3$ content was associated with the Burren Series Rendzinas, with content ranging between 3.3 and 69.7% (Table 2.23). Fen Peats also had significantly greater pH than the Kilcolgan Series Rendzinas and the Gleys however $CaCO_3$ content did not vary significantly among these three soil types (Table 2.22). OM and Inorg contents also varied highly significantly among the four soil types with Fen Peats having a higher mean OM content (Figure 2.28c) than the Gleys, Burren Series Rendzinas and Kilcolgan Series Rendzinas. The Burren Series Rendzinas also had higher mean OM content than the Coole Garryland Gleys ($p \leq 0.05$, Table 2.22) and Kilcolgan Series Rendzinas ($p \leq 0.05$, Table 2.22) (Figure 2.26c). The Gleys and Kilcolgan Series Rendzinas had significantly higher mean inorganic contents than the Fen Peats and Burren Series Rendzinas (Table 2.22).

Mean N_t concentrations did not differ significantly ($p > 0.05$, Table 2.21) among the four turlough soil types even though the Fen Peats had a higher mean N_t content (6402 mg l^{-1}) than the other three soil types (Figure 2.26e). A significant difference was not detected, most likely due to the high degree of variation associated with both the Burren Series Rendzinas and the Fen Peats. Mean P_t concentrations varied significantly ($p \leq 0.001$, Table 2.21) among the four soil types and were significantly higher (Bonferroni *post-hoc* test, $p \leq 0.01$, Table 2.22) in the two Coole Garryland soil types (Gleys and Kilcolgan Series Rendzinas) than the two soil types from the East Burren (Fen Peats and Burren Series Rendzinas). The greatest degree of variation in P_t status is associated with the Fen Peats where concentrations range from 74-642 mgl^{-1} (Figure 2.26f). No significant differences in P_{feo} or P_m concentrations were detected among the soil types (log transformed data, $p > 0.05$, Table 2.21), most likely due to the high degree of variation in P_{feo} and P_m concentrations associated with each soil type. Concentrations of P_{feo} differed by an order of magnitude in the Burren Series Rendzinas (2.6-30.1 mg l^{-1}, Table 2.20) resulting in a high degree of variability (Figure 2.26g). A similar range of concentrations (2.9-26.5 mg l^{-1}) occurred in the Gleys. K_t concentrations varied significantly (log transformed data, $p \leq 0.001$, Table 2.21) among the four soil types. K_t concentrations were significantly higher (Bonferroni *post-hoc* test, $p \leq 0.01$, Table 2.22) in the two Coole Garryland G soil types (Gley and Kilcolgan Series Rendzinas) than the two soil types from the East Burren (Fen Peats and Burren Series Rendzinas). No significant differences in K_t concentrations among the Fen Peats and Burren Series Rendzinas or Gleys and Kilcolgan Series Rendzinas were detected (Figure 2.26h). The greatest range in K_t concentrations was associated with the former two soil types. K_t concentrations differ by an order of magnitude in the Burren Series Rendzinas (203-2141 mg l^{-1}) and by two orders of magnitude in the Fen Peats (45-2589 mg l^{-1}) (Table 2.23).

The mean P_t status of the Peat-marls and Marls was 274 mg l^{-1} and 313 mg l^{-1} respectively (Table 2.23). The N_t status of the Peat-marls was within the range of the other soil types hower the Marls had a markedly lower mean concentration (3595 mg l^{-1}). Both soil types were also associated with extremely low mean K_t concentrations (Table 2.23). There was no obvious distinction between the P_{feo} and P_m status of the Peat-marls or Marls in comparison to the other soil types. The River-silt collected from Coole Turlough had an unusual combination of soil properties. This sample had elevated concentrations of P_t and K_t and extremely low P_m and N_t concentrations. This sample was collected from the shore of Coole Lough.

Table 2.12: Summary of soil types sampled within each turlough within each catchment. CE = Inse Woods, Coole; GC = Garryland; CG = Caherglassaun; HH = Hawkhill, KE = Knockaunroe; GT = Gortlcka, CO = Cooloorta; CR = Lough Cuil Reasc.

	Coole-Garryland				**East Burren**				**Total**
Broad Soil Group	CE	GD	CG	HH	KE	GT	CO	CR	
Kilcolgan Series Rendzina		3	4	4					11
Gley	8	4	4	3					19
Alluvium	1								1
Burren Series Rendzina					5	3	3	1	12
Fen Peat					3	5	3	1	12
Peat-marl					3				3
Marl					2				2

Table 2.13: Soil descriptions, sampling location and associated vegetation types for Hawkhill. Vegetation Zones (after Goodwillie1992): 5B = *Potentilla reptans* (spp. poor); 6A = Dry *Carex nigra*. *See footnote for explanations of colour, texture and organic matter.

Code	Location	Vegetation Zone	Colour	Texture	Organic matter	pH	%0M	$\%CaCO_3$	Soil Depth (cm)	Broad Soil Group
HH1	Upper	5B	Brown (10 YR 4/3)	Loam	Semi-fibrous	7.5	17.2	3.8	15	Rendzina, Kilcolgan series
HH2	Upper	5B	Brown (10 YR 4/3)	Loam	Semi-fibrous	7.2	22.1	5.9	20	Rendzina, Kilcolgan series
HH3	Middle	5B	Brown (10 YR 4/3). Few, fine flecks of shell marl (10 YR 8/1).	Loam	Semi-fibrous	7.3	20.6	5.7	19	Rendzina, Kilcolgan series
HH4	Middle	5B	Brown (10 YR 4/3). Few, fine flecks of shell marl (10 YR 8/1).	Loam	Semi-fibrous	7.3	17.6	3.4	21	Rendzina, Kilcolgan series
HH5	Middle	5B	Brown (10 YR 4/3) with brownish yellow mottles (10 YR 6/6). Common, very fine, distinct; sharp. Few, fine flecks of shell marl (10 YR 8/1).	Clay loam	Semi-fibrous	7.2	24.1	5.8	43	Gley
HH6	Lower	5B	Brown (10 YR 4/3) with brownish yellow mottles (10 YR 6/6). Common, very fine, distinct; sharp. Common, fine flecks of shell marl (10 YR 8/1).	Clay loam	Fibrous	7.5	25.6	19.1	45	Gley
HH7	Lower	6A	Very dark grey (10 YR 3/1). Many, medium flecks of snail shell marl (10 YR 8/1).	Clay loam	Fibrous	7.8	32.6	10.9	51	Gley

***Colour**: Soil matrix, mottling and shell marl were decsribed using Munsell Soil Colour Charts. Mottle Abundance; None, Few (2% of matrix), Common (2-20% of matrix), Many, (20-40% of matrix), Very many (> 40% matrix). Mottle Size; Extremely fine (< 1 mm), Very fine (1-2 mm), Fine (2-5 mm), Medium (5-15 mm), Coarse (> 15 mm). Mottle Contrast; Feint (indistinct), Distinct (readily seen), Prominent (conspicuous). Mottle Boundaries; Sharp, Clear, Diffuse. **Texture** : Loam; soil moulds readily when moist but sticks slightly to fingers, though some grittiness from a sand fraction is still obvious, Clay loam; sticky when moist, with just a slight sand fraction still detectable by its gritty contribution. **Organic matter**: organic matter was described as Semi-fibrous (partly decomposed fibres which are largely destroyed by rubbing) or Fibrous (large amounts readily identifiable plant remains).

Table 2.14: Soil descriptions, sampling location and associated vegetation types for Caherglassaun. Vegetation Zone: 5B = *P. reptans* (spp. poor); 2A = *Lolium* grassland; 6A = Dry *Carex nigra*. See Section 2.2.5 for corresponding information on soil colour, texture and nature of OM. *See footnote for explanation of colour texture and organic matter.

Code	Location	Vegetation Zone	Colour	Texture	Organic matter	pH	%0M	%CaCO$_3$	Soil Depth (cm)	Broad Soil Group
CG1	Upper	5B	Brown (10 YR 4/3)	Sandy loam	Semi-fibrous	6.0	13.0	3.3	14	Rendzina, Kilcolgan series
CG2	Upper	2A	Brown (10 YR 4/3)	Sandy loam	Semi-fibrous	5.8	16.2	6.9	19	Rendzina, Kilcolgan series
CG3	Middle	5B	Brown (10YR 4/3)	Sandy clay loam	Semi-fibrous	6.6	14.2	3.8	21	Rendzina, Kilcolgan series
CG4	Middle	2A	Brown (10 YR 4/)	Sandy clay loam	Semi-fibrous	6.7	14.7	5.3	19	Rendzina, Kilcolgan series
CG5	Middle	6A	Dark brown (10 3/3) with dark yellowish brown mottles (10 4/6). Many, extremely fine, distinct, sharp	Sandy clay loam	Semi-fibrous	6.7	14.1	4.1	31	Gley
CG6	Middle	2A	Dark brown (10 3/3) with dark yellowish brown mottles (10 4/6). Many, extremely fine, distinct, sharp	Sandy clay loam	Semi-fibrous	5.5	15.8	6.4	37	Gley
CG7	Lower	6A	Brown (10 YR 4/3) with yellowish brown mottles (10 YR 5/8). Common,very fine, distinct,clear.	Silty clay loam	Semi-fibrous	7.7	14.4	10.3	33	Gley
CG8	Lower	2A	Dark brown (10 YR 3/3) with dark yellowish brown mottles (10 YR 4/6). Many, extremely fine, distinct, diffuse.	Clay loam	Semi-fibrous	5.5	12.4	5.0	47	Gley

***Colour**: Soil matrix, mottling and shell marl were decsribed using Munsell Soil Colour Charts. Mottle Abundance; None, Few (2% of matrix), Common (2-20% of matrix), Many, (20-40% of matrix), Very many (> 40% matrix). Mottle Size; Extremely fine (< 1 mm), Very fine (1-2 mm), Fine (2-5 mm), Medium (5-15 mm), Coarse (> 15 mm). Mottle Contrast; Feint (indistinct), Distinct (readily seen), Prominent (conspicuous). Mottle Boundaries; Sharp, Clear, Diffuse. **Texture** : Sandy Loam; sand fraction feel is obvious but the soil moulds readily when sufficiently moist, without stickiness, Sandt Clay Loam; has sufficient clay to be quite sticky when moist, but the presence of a gritty sand fraction is still an obvious feature, Silty Clay Loam; less sticky than silty clay or clay loam, with elements of a slight sandy feel and a soapy feel due to the fraction Clay loam; sticky when moist, with just a slight sand fraction still detectable by its gritty contribution. **Organic matter**: organic matter was described as Semi-fibrous (partly decomposed fibres which are largely destroyed by rubbing) or Fibrous (large amounts readily identifiable plant remains).

Table 2.15: Soil descriptions, sampling location and associated vegetation types for Garryland. Vegetation Zone: 5B = *P. reptans* (spp. poor); 6A = Dry *C. nigra*; 6D = Peaty *C. nigra*; 11A = Reed Bed. *See footnote for explanation of colour, texture and organic matter.

Code	Location	Vegetation Zone	Colour	Texture	Organic matter	pH	%OM	%$CaCO_3$	Soil Depth (cm)	Broad Soil Group
GD1	Upper	5B	Dark yellowish brown (10 YR 3/4)	Loam	Semi-fibrous	5.7	12.4	4.9	20	Rendzina, Kilcolgan series
GD2	Upper	5B	Brown (10 YR 4/3)	Loam	Semi-fibrous	5.8	15.1	6.4	19	Rendzina, Kilcolgan series
GD3	Middle	5B	Dark yellowish brown (10 YR 3/4)	Clay loam	Semi-fibrous	6.1	19.5	5.8	20	Rendzina, Kilcolgan series
GD4	Middle	5B	Brown (10 YR 4/3) with yellowish brown mottles (7.5 YR 5/6). Common, extremely fine, distinct, sharp.	Clay loam	Semi-fibrous	6.3	18.6	7.1	34	Gley
GD5	Lower	6A	Brown (10 YR 4/3) with brownish yellow mottles (10 YR 6/8). Many, very fine, distinct, sharp.	Silty clay loam	Semi-fibrous	6.3	22.4	16.9	36	Gley
GD6	Lower	6D	Brown (10 YR 4/3) with yellowish brown mottles (10 YR 5/6). Common, extremely fine, distinct, sharp.	Clay loam	Semi-fibrous	7.8	17.5	9.8	39	Gley
GD7	Lower	11A	Gley 1 5/1 greenish grey with brownish yellow mottles (7.5 YR 6/8). Many, fine, prominent, diffuse.	Silt	Fibrous	7.3	17.1	7.2	31	Gley

***Colour**: Soil matrix, mottling and shell marl were decsribed using Munsell Soil Colour Charts. Mottle Abundance; None, Few (2% of matrix), Common (2-20% of matrix), Many, (20-40% of matrix), Very many (> 40% matrix). Mottle Size; Extremely fine (< 1 mm), Very fine (1-2 mm), Fine (2-5 mm), Medium (5-15 mm), Coarse (> 15 mm). Mottle Contrast; Feint (indistinct), Distinct (readily seen), Prominent (conspicuous). Mottle Boundaries; Sharp, Clear, Diffuse. **Texture** : Loam; soil moulds readily when moist but sticks slightly to fingers, though some grittiness from a sand fraction is still obvious, Clay Loam; sticky when moist, with just a slight sand fraction still detectable by its gritty contribution, Silty clay loam; less sticky than silty clay or clay loam, with elements of a slight sandy feel and a soapy feel due to the fraction, Silt; dominated entirely by smooth soapy feel of silt faction. **Organic matter**: organic matter was described as Semi-fibrous (partly decomposed fibres which are largely destroyed by rubbing) or Fibrous (large amounts readily identifiable plant remains). #

Table 2.16: Soil descriptions, sampling location and associated vegetation types for Coole. Vegetation Zone: 5B = *P. reptans* (spp. poor); 7A = *P. amphibium*(grassy). *See footnote for explanation of colour, texture and organic matter.

Code	Location	Vegetation Zone	Colour	Texture	Organic matter	pH	%OM	$\%CaCO_3$	Soil Depth (cm)	Broad soil group
CE1	Upper	5B	Brown (10 YR 4/3) with yellowish brown mottles (10 YR 5/6). Few, very fine, feint, diffuse.	Clay loam	Semi-fibrous	6.3	15.1	5.9	35	Gley
CE2	Upper	5B	Greyish brown (10YR 5/2) with dark yellowish brown mottles (10YR 4/6). Few, very fine, feint, diffuse.	Clay loam	Semi-fibrous	6.1	20.1	6.4	39	Gley
CE3	Middle	5B	Brown (10 YR 4/3)	Clay loam	Semi-fibrous	6.2	15.2	5.8	36	Gley
CE4	Middle	5B	Greyish brown (10 YR 5/2) with yellowish brown mottles (10 YR 5/4). Few, extremely fine, feint, clear.	Clay loam	Semi-fibrous	6.0	14.4	6.7	29	Gley
CE5	Lower	5B	Brown (10 YR 5/3) with dark yellowish brown mottles (10 YR 4/6). Few, very fine, feint diffuse.	Clay loam	Semi-fibrous	6.9	19.2	5.2	46	Gley
CE6	Lower	5B	Very dark grey (10YR 3/1) with yellowish brown mottles (10 YR 5/4) Few, very fine, feint diffuse	Clay loam	Semi-fibrous	6.5	19.6	6.8	42	Gley
CE7	Lower (Riverbank)	7A	Very dark greyish brown (10YR 3/2)	Silty clay	Semi-fibrous	8.3	6.2	46.2	15	Riversilt
CE8	Lower (Riverbank)	5B	Brown (10 YR 4/3) with yellowish brown mottles (10 YR 5/6). Few, very fine, feint diffuse.	Clay loam	Semi-fibrous	6.6	21.1	4.6	32	Gley
CE9	Lower (Riverbank)	5B	Greyish brown (10 YR 5/2) with yellowish brown mottles (10 YR 5/4). Common, extremely fine, distinct, sharp.	Clay loam	Semi-fibrous	7.3	20.8	8.6	49	Gley

Table 2.17: Soil descriptions, sampling location and associated vegetation types for Knockaunroe. Vegetation Zone: 5B = *P. reptans* (spp. poor); 7A = *P. amphibium* (grassy) ; 6A = Dry *C. nigra*; 7B = Tall Sedge; 9C = Marl Pond ; 6D = Peaty *C. nigra*; 8C = *Cladium* Fen . *See footnote for explanation of colour, texture and organic matter.

Code	Location	Vegetation Zone	Colour	Texture	Organic matter	pH	%OM	$\%CaCO_3$	Soil Depth	Broad soil group
KE1	Upper	5B	Very dark brown (10 YR 2/2).	Organic	Fibrous	7.9	45.0	6.7	11	Rendzina, Burren series
KE2	Upper	7A	Very dark brown (10 YR 2/2).	Organic	Fibrous	8.9	13.3	42.2	12	Rendzina, Burren series
KE3	Middle	5B	Dark brown (10 YR 3/3). Common, very fine flecks of snail shell marl (10 YR 8/1).	Organic	Fibrous	8.4	35.1	36.9	7	Rendzina, Burren series
KE4	Middle	7B	Dark brown (10 YR 3/3) Common, very fine flecks of snail shell marl (10 YR 8/1).	Organic	Fibrous	8.8	11.3	55.6	13	Rendzina, Burren series
KE5	Middle	6A	Dark brown (10 YR 3/3). Common, very fine flecks of snail shell marl (10 YR 8/1).	Organic	Fibrous	8.3	19.9	69.6	18	Rendzina, Burren series
KE6	Middle	6A	Dark brown (10 YR 3/3) Many, very fine flecks of snail shell marl (10 YR 8/1).	Silt loam	Fibrous	8.5	23.7	61.4	37	Peat--marl
KE7	Middle	7A	Grey (10 YR 5/1). Many, medium flecks of snail shell marl (7.5 YR 8/1).	Silt loam	Fibrous	8.7	15.8	67.6	42	Peat-Marl
KE8	Lower	9C	Grey (10 YR 5/1). Many, medium flecks of snail shell marl (10 YR 8/1).	Silt	Semi-fibrous	8.6	13.3	78.4	55	Marl
KE9	Lower	9C	Grey (10 YR 5/1) Many, medium flecks (abundant)	Silt loam	Semi-fibrous	8.7	24.4	60.0	53	Peat--marl

			of snail shell marl (10 YR 8/1)							
KE10	Lower	9C	Grey (10 YR 5/1). Many, medium flecks of snail shell marl (10 YR 8/1)	Silt	Semi-fibrous	8.8	10.7	70.5	57	Marl
KE11	Lower	6D	Dark brown (10 YR 3/3). Common, very fine flecks of snail shell marl (7.5 YR 8/1).	Organic	Fibrous	7.4	86.4	4.4	42	Fen peat
KE12	Lower	8C	Dark brown (10 YR 3/3). Common, fine flecks of snail shell marl (10 YR 8/1).	Organic	Fibrous	7.3	82.7	4.8	62	Fen peat
KE13	Lower	7B	Dark brown (10 YR 3/3). Common, very fine flecks (common) of snail shell marl (10 YR 8/1).	Silt	Fibrous	8.5	34.0	9.5	67	Fen peat

***Colour**: Soil matrix, mottling and shell marl were decsribed using Munsell Soil Colour Charts. Shell Marl Abundance; None, Few (2% of matrix), Common (2-20% of matrix), Many, (20-40% of matrix), Very many (> 40% matrix). Fleck size Size; Extremely fine (< 1 mm), Very fine (1-2 mm), Fine (2-5 mm), Medium (5-15 mm), Coarse (> 15 mm). **Texture** : Silt loam; has moderate plasticity but little stickiness, with the smooth soapy feel of silt being conspicuous, Silt; dominated entirely by smooth soapy feel of silt faction, Organic; high organic content, not fitting into any of the above classes. **Organic matter**: organic matter was described as Semi-fibrous (partly decomposed fibres which are largely destroyed by rubbing) or Fibrous (large amounts readily identifiable plant remains).

Table 2.18: Soil descriptions, sampling location and associated vegetation types for Gortlecka. Vegetation Zone: 4W = *Rhamnus* wood; 2B = Poor grassland; 6A = Dry *Carex nigra*. *See footnote for explanation of colour, texture and organic matter.

Code	Location	Vegetation Zone	Colour	Texture	Organic matter	pH	%OM	% $CaCO_3$	Soil Depth (cm)	Broad soil group
GT1	Upper	3W	Dark brown (10 YR 3/3)	Organic	Semi-fibrous	7.8	34.3	4.1	9	Rendzina, Burren series
GT2	Upper	3W	Dark brown (10 YR 3/3)	Organic	Semi-fibrous	7.8	21.5	42.9	18	Rendzina, Burren series
GT3	Upper	2B	Dark brown (10 YR 3/3)	Organic	Semi-fibrous	6.7	29.8	4.5	21	Rendzina, Burren series
GT4	Middle	6A	Dark brown (10 YR 3/3). Common, very fine flecks of snail shell marl (10 YR 8/1).	Silt loam	Fibrous	7.5	40.9	5.1	29	Fen peat
GT5	Middle	2B	Dark brown (10 YR 3/3). Common, very fine flecks of snail shell marl (10 YR 8/1).	Silt loam	Fibrous	8.0	37.6	27.5	30	Fen peat
GT6	Middle	6A	Very dark grey (10 YR 3/1)	Silt loam	Fibrous	7.4	38.2	5.5	42	Fen peat
GT7	Lower	6A	Dark grey (10 YR4 /1)	Silt loam	Fibrous	7.7	39.7	5.3	37	Fen peat
GT8	Lower	2B	Dark grey (10 YR4 /1)	Silt loam	Fibrous	7.7	32.0	5.4	36	Fen peat

***Colour**: Soil matrix, mottling and shell marl were decsribed using Munsell Soil Colour Charts. Shell Marl Abundance; None, Few (2% of matrix), Common (2-20% of matrix), Many, (20-40% of matrix), Very many (> 40% matrix). Fleck size Size; Extremely fine (< 1 mm), Very fine (1-2 mm), Fine (2-5 mm), Medium (5-15 mm), Coarse (> 15 mm). **Texture** : Silt loam; has moderate plasticity but little stickiness, with the smooth soapy feel of silt being conspicuous, Organic; high organic content, not fitting into any of the above classes. **Organic matter**: organic matter was described as Semi-fibrous (partly decomposed fibres which are largely destroyed by rubbing) or Fibrous (large amounts readily identifiable plant remains).

Table 2.19: Soil descriptions, sampling location and associated vegetation types for Cooloorta. Vegetation Zone: 3B = Sedge Heath; 8C = *Cladium* Fen; 5D = Sedge Fen. *See footnote for explanation of colour, texture and organic matter.

Code	Location	Vegetation Zone	Colour	Texture	Organic matter	pH	%OM	%$CaCO_3$	Soil Depth (cm)	Broad soil group
CO1	Upper	3B	Brown (10 YR 4/3)	Organic	Fibrous	7.0	21.1	3.3	21	Rendzina, Burren series
CO2	Upper	3B	Brown (10 YR 4/3)	Organic	Fibrous	6.7	20.3	3.5	11	Rendzina, Burren series
CO3	Middle	3B	Brown (10 YR 4/3)	Organic	Fibrous	8.2	30.3	19.0	17	Rendzina, Burren series
CO4	Middle	8C	Dark brown (10 YR 3/3) Common, fine flecks of snail shell marl (10 YR 8/1).	Organic	Fibrous	7.0	55.8	10.6	42	Fen Peat
CO5	Lower	5D	Dark brown (10 YR 3/3)	Organic	Fibrous	7.3	31.0	5.2	31	Fen Peat
CO6	Lower	5D	Dark brown (10 YR 3/3)	Organic	Fibrous	7.2	85.5	4.9	30	Fen Peat

***Colour**: Soil matrix, mottling and shell marl were decsribed using Munsell Soil Colour Charts. Shell Marl Abundance; None, Few (2% of matrix), Common (2-20% of matrix), Many, (20-40% of matrix), Very many (> 40% matrix). Fleck Size; Extremely fine (< 1 mm), Very fine (1-2 mm), Fine (2-5 mm), Medium (5-15 mm), Coarse (> 15 mm). **Texture** : Organic; high organic content, not fitting into any of the above classes. **Organic matter**: organic matter was described as Semi-fibrous (partly decomposed fibres which are largely destroyed by rubbing) or Fibrous (large amounts readily identifiable plant remains).

Table 2.20: Soil descriptions, sampling location and associated vegetation types for Lough Cuil Reasc. Vegetation Zone: 3C = Flooded pavement; 6B =Wet *Carex nigra*. *See footnote for explanation of colour, texture and organic matter.

Code	Location	Vegetation Zone	Colour	Texture	Organic matter	pH	%OM	$\%CaCO_3$	Soil Depth (cm)	Broad soil group
CR1	Upper	3C	Brown (10 YR 4/3). Few, fine flecks of snail shell marl (10 YR 8/1).	Organic	Fibrous	7.8	40.7	18.2	21	Rendzina, Burren series
CR2	Lower	6B	Very dark brown (10 YR 2/2). Few, fine flecks of snail shell marl (10 YR 8/1).	Organic	Fibrous	7.1	81.4	4.4	47	Fen Peat

***Colour**: Soil matrix, mottling and shell marl were decsribed using Munsell Soil Colour Charts. Shell Marl Flecks: Abundance; None, Few (2% of matrix), Common (2-20% of matrix), Many, (20-40% of matrix), Very many (> 40% matrix). Fleck Size; Extremely fine (< 1 mm), Very fine (1-2 mm), Fine (2-5 mm), Medium (5-15 mm), Coarse (> 15 mm). **Texture** : Organic; high organic content, not fitting into any of the above classes. **Organic matter**: organic matter was described as Semi-fibrous (partly decomposed fibres which are largely destroyed by rubbing) or Fibrous (large amounts readily identifiable plant remains).

Table 2.21: Analysis of variance summary of soil nutrient property variation among turlough soil types. Symbols: ns = $p > 0.05$; * = $p < 0.05$; **= $p < 0.01$; *** = $p < 0.0001$.

Source of variation			
	Soil type		
Variable	*df*	*F*	*p*
pH	3	10.3	***
%$CaCO_3$	3	5.9	**
%OM	3	25.4	***
%Inorg	3	11.5	***
N_t mg l^{-1} Soil	3	1.5	ns
P_t mg l^{-1} Soil	3	8.1	***
P_{feo} mg l^{-1} Soil	3	1.6	ns
P_m mg l^{-1} Soil	3	2.7	ns
K_t mg l^{-1} Soil	3	38.4	***

Table 2.22: Bonferroni post hoc summary for the soil property variation among soil types. BSR (Burren Series Rendzina); KSR (Kilcolgan Series Rendzina); G (Gley); FP (Fen Peat).

Post hoc comparison						
Variable	G-FP	BSR-FP	BSR-G	KSR-FP	KSR-G	KSR-RBS
pH	*	*	***	*	ns	***
%$CaCO_3$	ns	*	*	ns	ns	**
%OM	***	***	ns	***	ns	*
%Inorg	***	ns	*	***	ns	*
P_t mg l^{-1} Soil	*	ns	**	*	ns	**
K_t mg l^{-1} Soil	***	ns	***	***	ns	***

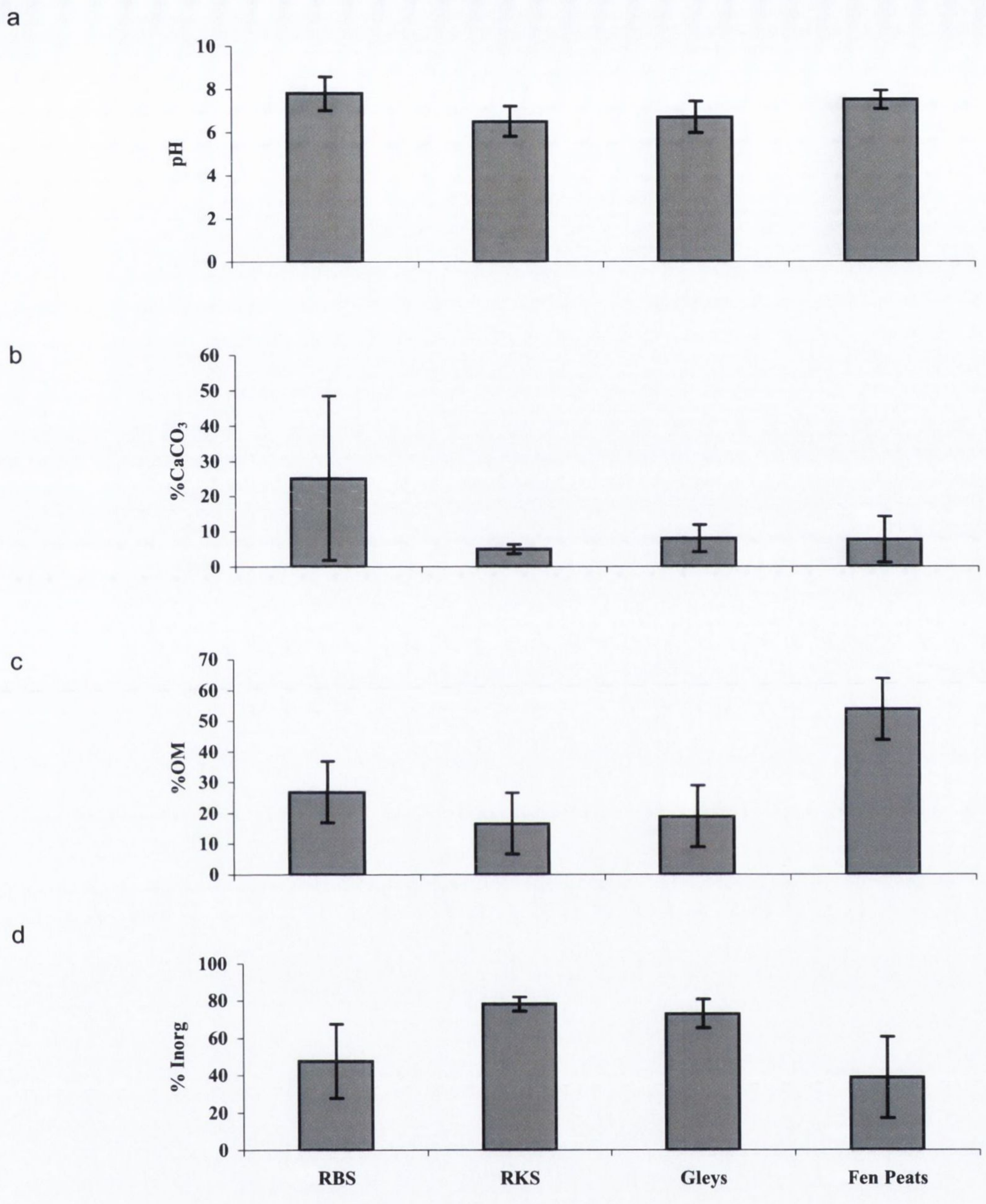

Figure 2.26: Variation in soil nutrient related properties among Rendzinas, Burren Series (RBS) (n=12), Rendzinas, Kilcolgan Series (RKS) (n=11), Gleys (n=19) and Fen Peats (n=12). a) pH; b) %$CaCO_3$, c) % OM and d) % Inorg.

e

f

g

h

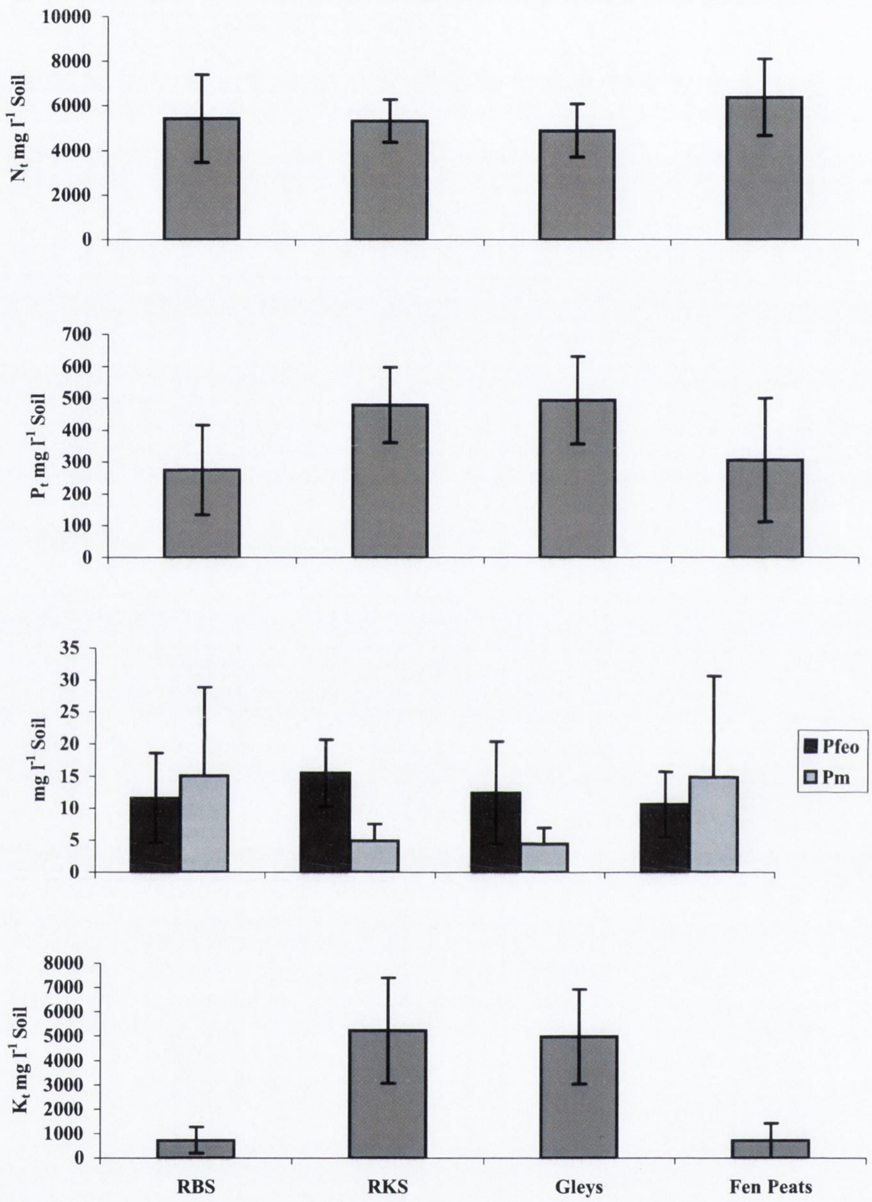

Figure 2.26: Variation in soil nutrient related properties among Burren Series Rendzinas (BSR) (n=12), Kilcolgan Series Rendzinas (KSR) (n=11), Gleys (n=19) and Fen Peats (n=12). e) N_t; f) P_t, g) P_{feo} and P_m and h) K_t.

Table 2.23: Summary statistics of pH, $CaCO_3$ (%), OM (%), Inorg (%), N_t, P_t, P_{feo}, P_m and K_t (mg l^{-1} Soil) for each soil type: (BSR) Burren Series Rendzina (n=12); (KSR) Kilcolgan Series Rendzina (n=11); (G) Gley (n=19); (FP) Fen Peat (n=12); (PM) Peat-marl (n=3); (M) Marl (n=2); (RS) River silt (n=1).

Statistic	pH	%$CaCO_3$	%OM	%Inorg	N_t	P_t	P_{feo}	P_m	K_t
(BSR)									
Mean	7.8	25.1	26.9	47.6	5436	276	11.6	4.9	733
SD	0.8	23.3	10.6	19.8	1962	141	7.0	2.6	534
Min	6.7	3.3	11.3	10.5	2430	133	2.6	0.8	203
Max	8.9	69.7	44.9	76.2	8518	634	30.1	8.3	2141
(KSR)									
Mean	6.5	5.0	16.6	78.4	5321	480	15.5	15.1	5226
SD	0.7	1.3	3.1	3.8	960	118	5.2	13.8	2171
Min	5.7	3.3	12.4	2.0	4498	307	8.2	0.5	1445
Max	7.5	6.9	22.1	83.7	7015	650	23.4	41.1	9051
(G)									
Mean	6.7	8.0	18.9	73.0	4899	495	12.4	4.4	4986
SD	0.7	3.9	4.9	7.7	1185	137	8.0	2.6	1944
Min	5.5	4.1	12.4	55.4	2424	327	2.9	0.8	1540
Max	7.8	19.1	32.6	82.6	7656	782	26.5	11.5	8373
(FP)									
Mean	7.5	7.7	53.8	38.7	6402	306	10.6	14.5	718
SD	0.4	6.5	23.2	21.8	1720	195	5.1	15.7	711
Min	7.0	4.4	31.0	9.3	2225	74	2.9	0.84	45
Max	8.5	27.5	96.4	63.8	8363	642	17.8	40.5	2589
(PM)									
Mean	8.6	63.0	21.3	16.0	5136	274	11.2	9.9	401
SD	0.1	4.0	4.8	1.0	765	42	0.8	4.4	112
Min	8.5	60.1	15.8	15.0	4270	232	10.4	4.8	275
Max	8.7	67.6	24.4	17.0	5720	316	12.0	12.5	491
(M)									
Mean	8.7	74.5	12.0	13.5	3595	313	8.5	6.6	619
SD	0.1	5.6	1.8	7.8	540	28	4.9	3.5	387
Min	8.6	70.5	10.7	8.0	3213	293	5.0	4.1	345
Max	8.8	78.4	13.3	19.0	3976	332	11.9	9.1	892
(RS)									
	8.3	46.2	6.2	47.6	2219	1042	14.3	1.5	8696

2.3.3 Relationships between turlough vegetation types and soil nutrient-related properties.

The dendrogram presented in Figure 2.27 illustrates 3 main, well defined vegetation groups (Group 1, Group 2 and Group 4). Group 3 represents a group of samples which were difficult to classify, as indicated by the long stems. The variation in sum of significant indicator values (IndVals; closed squares) and number of significant indicator species (closed diamonds) as determined by Indicator Species Analysis, for different stages of the cluster cycle is presented in Figure 2.28. The ISA did not reveal clearly defined local maxima of the sum of significant IndVals and number of significant indicator species, although Figure 2.28 indicated that stage 4 would provide informative levels of clustering. Visual inspection of the NMS ordination was used to externally validate the partition of the dataset. NMS ordination of vegetation releves found a three-dimensional solution (Figures 2.29-2.31). Stress on this solution was 17.3% (less than the 20% threshold set by McCune and Grace, 2002) with a final instability of 0.00121 with 400 iterations. The three axes represented 78.2% of variation in the dataset (Axis 1: r^2=0.229; Axis 2: r^2=0.331; Axis 3: r^2 = 0.222). Monte Carlo tests revealed good structure in the data as stress related to each axis was significantly less in the real data than in the randomised data (Axis 1, 2 and 3: $p = 0.0196$). Ordination diagrams of Axes 1 and 2, Axes 1 and 3 and Axes 2 and 3 are presented in Figure s 2.29, 2.30 and 2.31 respectively. Groups 1, 2 and 4 grouped together relatively well in the ordination, providing some validation of the cluster solution. Group 3, associated with long stems in the dendrogram, did not cluster well in the NMS ordination indicating a high level of dissimilarity among the releves within this group. Closer inspection of the species richness associated with these quadrats (Appendix E) revealed a possible explanation for this dissimilarity. Quadrats within this group had either a low species richness (< 5 species) or had a species richness between 10 and 17 with a low dominance of grass or sedge species. These factors make this group distinct from Groups 1,2 and 4 which are relatively species rich and dominated by grass or sedge species. Summary statistics of soil nutrient properties associated with each vegetation group are presented in Table 2.25. Additional soil type and elevation information is extracted from Tables 2.13 – 2.20. Each vegetation group was named after the species (or one of the species) with the highest IndVals within that group; these names are simply intended to succinctly distinguish and describe the related vegetation data: no direct reference to other classification systems is implied. A brief description of each group follows.

Ranunculus repens group (Group 1; n = 11)

This vegetation type occurs consists solely of releves assigned to the 5B (*Potentilla reptans* spp. poor) Goodwillie (1992) vegetation type which is indicative of upper and middle elevations. The associated soils were Kilcolgan Series Rendzinas and Gleys with loam textures and semi-fibrous organic matter. Gleying is a dominant feature however not all associated soils are gleyed. This vegetation type includes only releves from the Coole Garryland turloughs and includes releves taken from the highest elevations within these turloughs. The pH status ranged from 5.7 to 7.5 and $CaCO_3$ content ranged between 3.3 and 19.1%, however nine of the eleven releves assigned to this vegetation type had a $CaCO_3$ content less than 6%. The mean OM and Inorg contents associated with this group were 17.3% and 76.4% respectively (Table 2.25). Mean N_t was 4849 mgl^{-1} and mean P_t was 430 mg l^{-1}. P_{feo} exhibited a wide range of concentrations within this vegetation type, ranging between 2.9 and 17.5 mg l^{-1}. A wide range of K_t concentrations was also associated with this vegetation type (1445 – 9051 mg l^{-1}). Frequent and potentially dominant species (maximum Domin score $\geq$ 5) were *Agrostis capillaris* and *Ranunculus repens*. Other frequent species include *Leontodon autumnale*, *Agrostis stolonifera*, *Potentilla anserina* and *Filipendula ulmaria*.

Agrostis stolonifera group (Group 2; n = 13)

This vegetation type was associated with a wide range of elevations and reflected the full range of elevations (upper, middle, lower). It included releves assigned to the 5B (*P. reptans* spp. poor) Goodwillie vegetation type, however additional vegetation types included 2A (*Lolium* Grassland), 2B (Poor Grassland) and 3W (*Rhamnus* wood). The associated soils were generally Kilcolgan Series Rendzinas and Gleys with loam textures and semi-fibrous organic matter content. This vegetation type includes releves taken from Coole Garryland turloughs and Gortlecka turlough in the East Burren. The pH status ranges from 5.4 to 7.8 and the majority of releves had $CaCO_3$ content less than 10% (5.0-42.9%). The majority of OM contents ranged between 20-30%. N_t ranged between 4055 and 8180 mg l^{-1} and P_t concentrations ranged between 307 and 650 mg l^{-1}. Extreme ranges of P_{feo} and K_t were associated with this vegetation type (Table 2.25). Frequent and potentially dominant species (maximum Domin score $\geq$ 5) were *Agrostis stolonifera* and *Potentilla anserina*. Other frequent species include *Trifolium repens*, *Filipendula ulmaria* and *Ranunculus repens*.

Carex nigra group (Group 4; n = 18)

This vegetation type included a mix of releves from the Coole Garryland and East Burren catchments which were generally associated with the middle and lower turlough areas. Releves from the Coole Garryland catchment were all associated with the middle and lower turlough areas. This vegetation type included releves from a broad range of Goodwillie (1992) vegetation types: 6A (Dry *Carex nigra*), 3B (Sedge Heath), 5B (*P. reptans* spp. poor) 7A *Polygonum amphibium* (grassy), 2B (Poor grassland) 3C (flooded pavement) and 7B (Tall Sedge). Predominant soil types included Gleys, Burren Series Rendzinas, Fen Peats, and Peat-marls. This vegetation type is associated with organic rich, base-rich soils. The pH status ranges from 6.3 – 8.7 and the majority of the associated soils have organic textures with fibrous OM content and silty textures. The mean associated Inorg, OM and $CaCO_3$ contents were 48.9%, 25.6% and 25.2% respectively (Table 2.25). Wide ranges of N_t, P_t, P_{feo} and K_t were associated with this vegetation type (Table 2.25). Frequent and potentially dominant species (maximum Domin score ≥ 5) were *Carex nigra*, *Agrostis stolonifera* and *Potentilla anserina.*

Group 3, n = 18

This vegetation type includes releves from a wide range of vegetation types identified by Goodwillie (1992), including 3B Sedge Heath, 5D Sedge Fen, 6B Wet *Carex nigra,* 5B *P. reptans* spp. poor, 9C Marl Pond, 6A *Dry C. nigra,* 4W *Frangula alnus/Potentilla fruticosa,* 6D Peaty *Carex nigra,* 8C *Cladium* Fen, 7B Tall Sedge, 11 A Reed Bed and 7A *Polygonum amphibium* (grassy). This wide range of vegetation types is reflected in the wide ranges of soil nutrient variables associated with this group (Table 2.25).

pH and $CaCO_3$ were significantly positively correlated with Axis 1 ($p \leq 0.01$, Table 2.26) and this axis therefore represents an alkalinity gradient. A transition from grass dominated vegetation types (Groups 1 and 2) to the sedge dominated vegetation type (Group 4) occurred along Axis 1 and overall there was good separation between Groups 1 and 2 from Group 4 along Axis 1 (Figure 2.30). Axis 2 correlated positively with OM ($p \leq 0.01$), pH ($p \leq 0.01$) and negatively with inorganic content ($p \leq 0.01$) and represents an organic/mineral gradient. Axis 2 was also significantly negatively correlated with K_t ($p \leq 0.01$) and P_t ($p \leq 0.01$) and therefore also represents a nutrient gradient. Axis 2 is heavily influenced by releves within the Transitional Group 3 and it is considered that Axes 1 and 3 present the best representation of the data. pH and $CaCO_3$ were significantly positively correlated with Axis 3. Inorganic content and K_t were significantly negatively correlated with Axis 3 (Table 2.26). Group 1 is moderately well separated from Groups 2 and 4 along Axis 3. N_t and P_{feo} did not explain any variation along any axes.

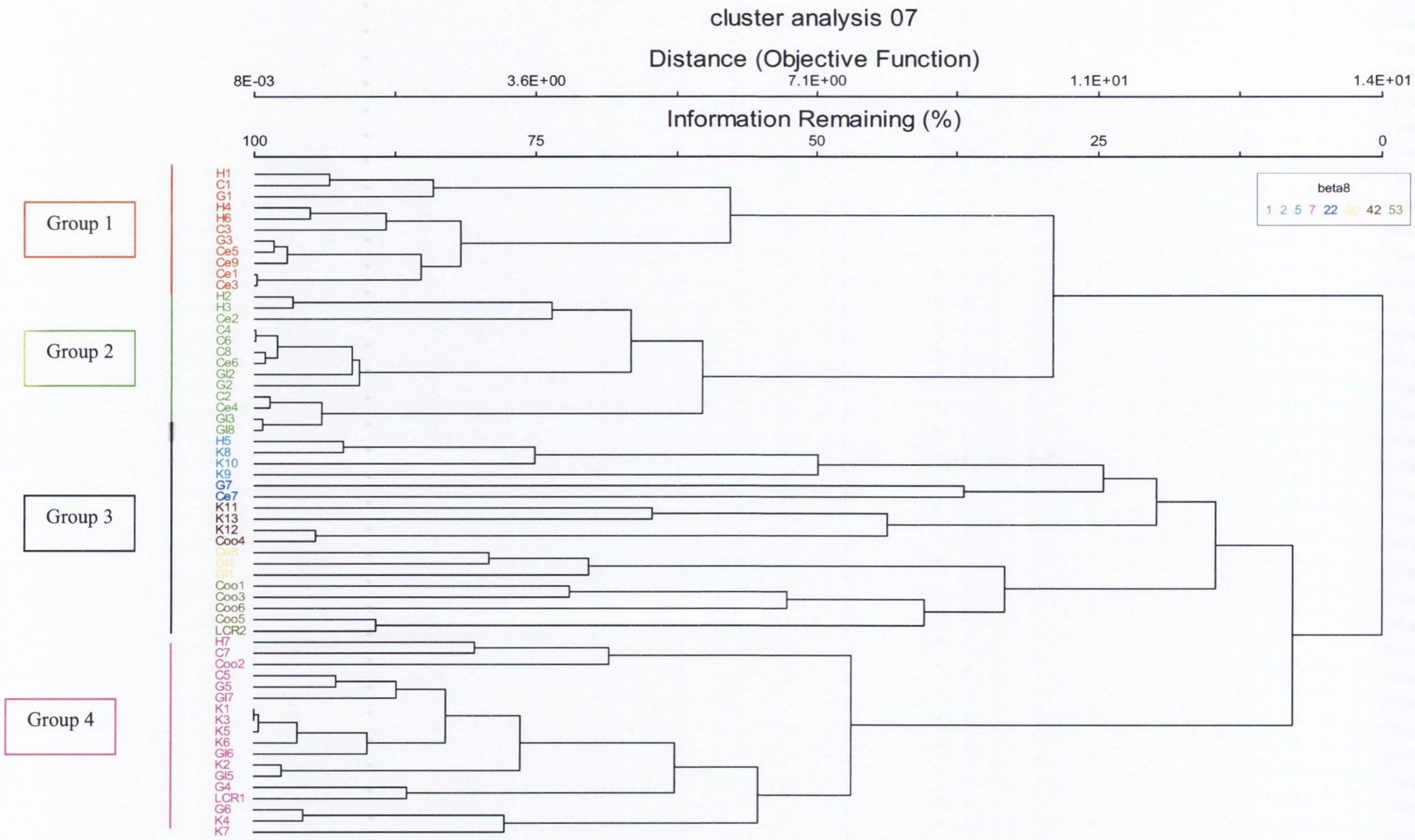

Figure 2.27: Dendrogram showing the relationship among 60 vegetation releves from the Coole Garryland catchment and East Burren catchment..

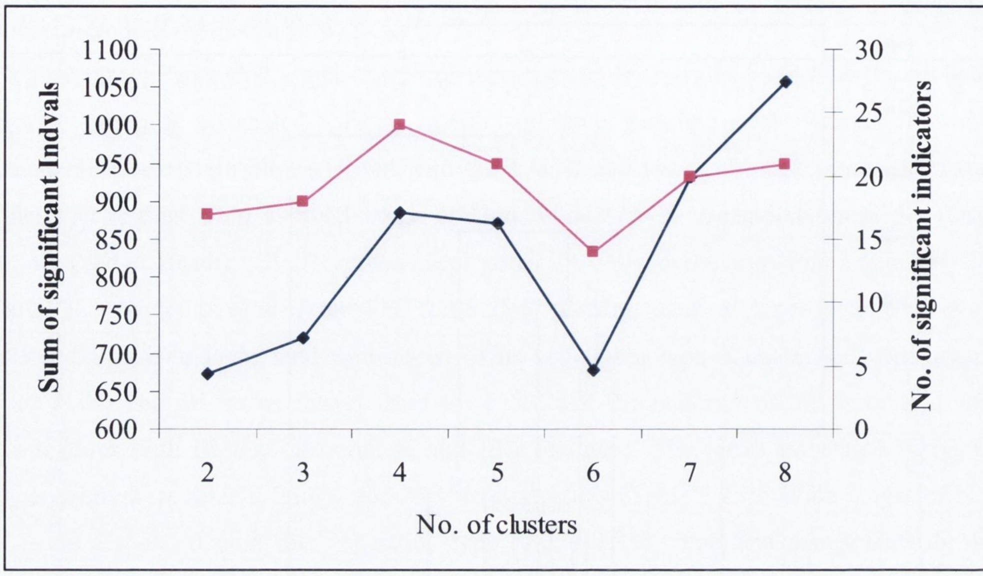

Figure 2.28: Variation in sum of significant IndVals (closed squares) and number of significant indicator species (closed diamonds) as determined by Indicator Species Analysis, for different stages of the cluster cycle.

Figure 2.29: NMS ordination plot of 60 vegetation releves along Axes 1 and 2. Group 1= *Ranunculus repens* group; Group 2 = *Agrostis stolonifera* group; Group 3 = Transitional group; Group 4 = *Carex nigra* group.

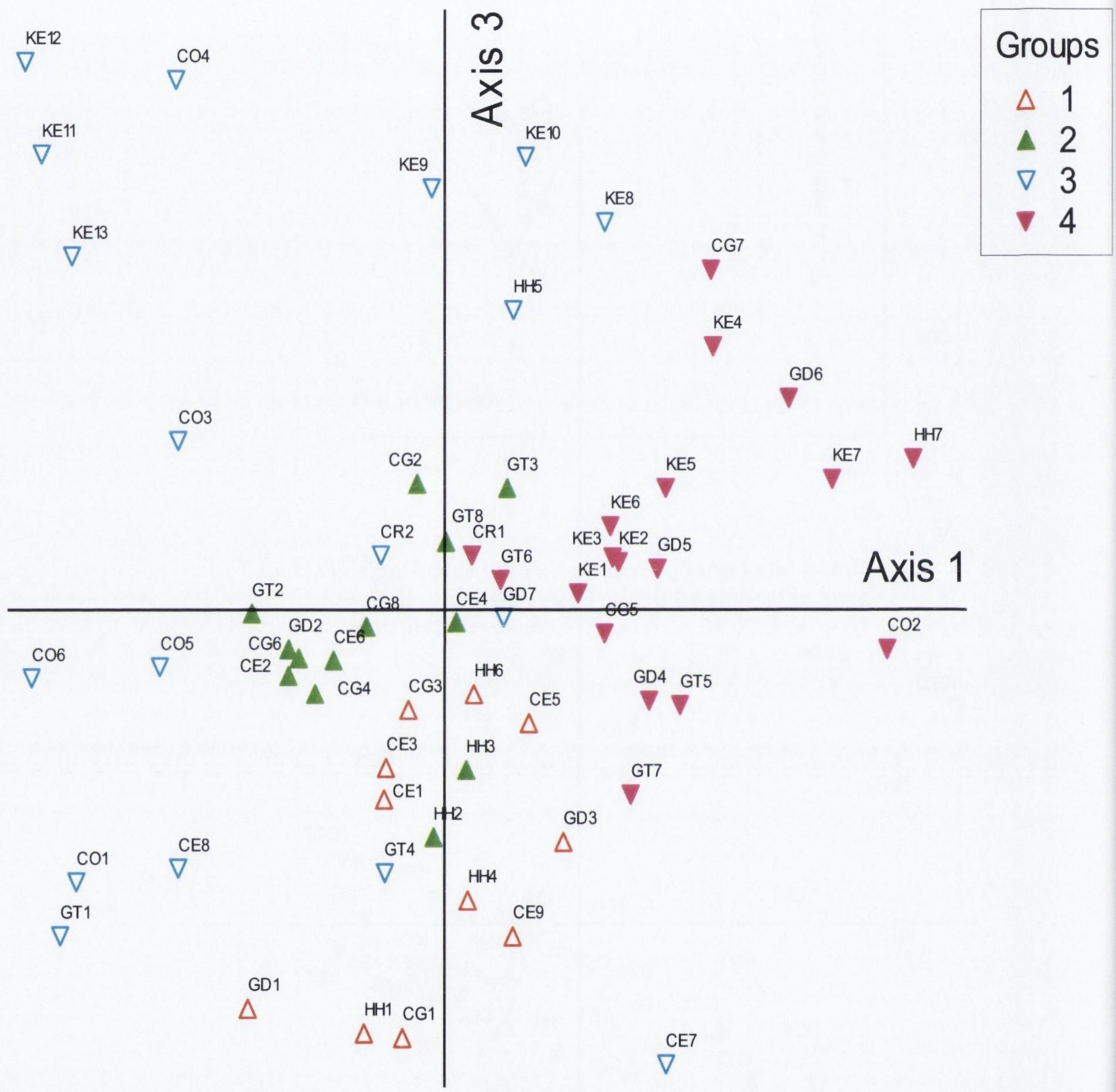

Figure 2.30: NMS ordination plot of 60 vegetation releves along Axes 1 and 3. Group 1= *Ranunculus repens* group; Group 2 = *Agrostis stolonifera* group; Group 3 = Transitional group; Group 4 = *Carex nigra* group.

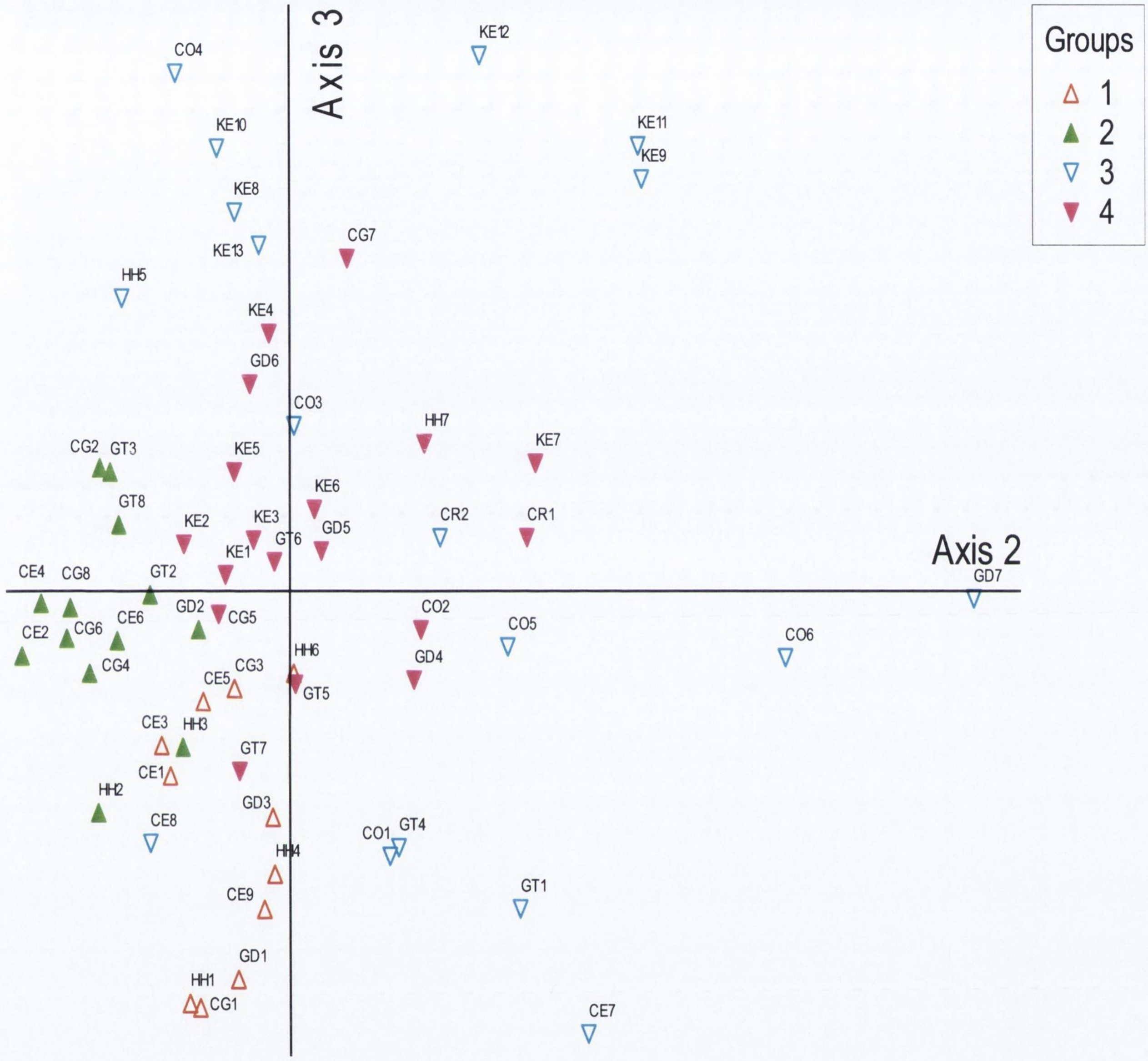

Figure 2.31: NMS ordination plot of 60 vegetation releves along Axes 2 and 3. Group 1= *Ranunculus repens* group; Group 2 = *Agrostis stolonifera* group; Group 3 = Transitional group; Group 4 = *Carex nigra* group.

Table 2.25: Summary statistics of pH, %$CaCO_3$, %OM, %Inorg, N_t, P_t, P_{feo}, P_m and K_t (mg l^{-1} Soil) for each vegetation group: (Group 1) *Ranunculus repens* group (n=11); (Group 2) *Agrostis stolonifera* group (n=13); Group 3 (n=18); (Group 4) *Carex nigra* group (n=18).

Statistic	pH	%$CaCO_3$	%OM	%Inorg	N_t	P_t	P_{feo}	K_t
(Group 1)								
Mean	6.7	6.3	17.3	76.4	4849	430	8.9	5251
SD	0.7	4.5	3.9	7.9	895	77	4.9	2148
Min	5.7	3.3	12.4	55.4	3867	327	2.9	1445
Max	7.5	19.1	25.6	83.7	6503	580	17.5	9051
(Group 2)								
Mean	6.5	8.8	19.6	71.6	5514	506	19.6	4878
SD	0.8	10.3	5.9	12.2	1333	121	6.2	2536
Min	5.4	5.0	12.4	35.6	4055	307	8.2	688
Max	7.8	42.9	32.0	82.6	8180	650	30.1	8960
(Group 3)								
Mean	7.7	19.3	38.9	41.9	5099	346	9.5	1593
SD	0.7	25.4	27.3	26.0	1643	254	4.7	2355
Min	6.6	4.1	6.2	8.3	2225	74	2.6	45
Max	8.8	78.4	86.4	75.7	6988	1042	17.8	8696
(Group 4)								
Mean	7.7	25.2	25.6	48.9	5650	368	11.9	1716
SD	0.8	23.9	11.2	22.6	1926	183	5.1	1836
Min	6.3	3.5	11.3	10.5	2424	132	3.0	274
Max	8.7	69.6	40.7	81.7	8518	642	23.2	5876

Table 2.26: Rank-order associations (Kendall tau) between soil nutrient properties and vegetation NMS ordination scores along Axes 1, 2 and 3 (see figures 2.30 – 2.33) (n=60). **= $p < 0.01$

	Axis 1	*p*	Axis 2	*p*	Axis 3	*p*
pH	0.232	**	0.289	**	0.258	**
OM %	-0.18	ns	0.236	**	0.132	ns
Inorg %	-0.093	ns	-0.305	**	-0.38	**
$CaCO_3$ %	0.32	**	0.053	ns	0.358	**
N_t mg l^{-1}	0.01	ns	0.069	ns	0.035	ns
P_t mg l^{-1}	0.173	ns	-0.275	**	-0.2	ns
P_{feo} mg l^{-1}	0.016	ns	-0.179	ns	-0.108	ns
K_t mg l^{-1}	0.034	ns	-0.323	**	-0.339	**

2.4 Discussion

2.4.1 Variation in soil nutrient-related properties and soil types among two contrasting catchment types

Turloughs associated with the two contrasting catchment types under investigation were found to differ in organic, calcareous and non-calcareous inorganic soil contents and in the nature of their soil types. Turloughs in the Coole Garryland catchment had lower organic matter and higher inorganic contents, independent of sampling location, than turloughs in the East Burren catchment. Coole Garryland soils were characterised by organic matter and inorganic contents indicative of a mineral condition, whereas East Burren organic matter and inorganic contents reflected an organic or peaty soil condition. It must be noted however that the mean organic matter content recorded for Coole Garryland (17.7%) is at the high end of the organic matter content diagnostic range (0-20%) for mineral soils (Mitsch and Gosselink, 2000). Turloughs from both catchments had distinctly different soil types which also reflected the peaty nature of soils within East Burren turloughs and the mineral condition of the Coole Garryland soils. Kilcolgan Series Rendzinas and Gleys were the dominant soil types associated with Coole Garryland turloughs, whereas Burren Series Rendzinas and Fen Peats were characteristic of the East Burren turloughs. East Burren turloughs were characterised by a wide range of calcareous contents which often reflected a highly calcareous condition, whilst within Coole Garryland a narrow, comparatively low range of calcareous contents were recorded. Peat-marls and Marls were associated with the East Burren, but these soil types were not recorded within the Coole Garryland turloughs. These differences in the nature of soils among catchments may be the result of a combination of the differing parent materials associated with each of the catchments and the differing hydrological and hydrochemical conditions induced by the contrasting nature of the karst aquifers. Turloughs within Coole Garryland are drift filled whilst turloughs in the East Burren lack drift. However, Gerrard (2000) states that it can be very difficult to assess the role of parent material in soil formation as parent material often only provides the framework within which other factors and processes operate. Birkeland (1984) has stressed that the influence of parent material appears to be greatest in the early stages of soil formation and in drier regions and that with time, other soil-forming factors, such as climate and biota, overwhelm the influence of parent material. Soil properties were described within the uppermost 10 cm and hydrological and hydrochemical factors are likely to exert a greater influence on soil properties at this depth than parent material. However, parent material was important in making the distinction between the Rendzinas among the catchments. Gerrard (2000) states that soil development on limestones is controlled to a great extent by the parent material and associated soils are commonly thin, fine grained and with a sharp contact with the bedrock.

The differences in Mg_t and Fe_t among the catchments is thought to be particularly related to the differing parent materials. Iron rich soils were associated with Coole Garryland and it is thought that the higher Fe_t contents are the result of the presence of drift derived parent materials and the iron rich waters feeding this catchment from the Slieve Aughty mountains. The limestone and marl parent materials associated with the East Burren, and the associated highly alkaline floodwaters, would be expected to produce soils low in Fe_t. MacGowran (1985) classified soil samples based on soil nutrient properties from sixteen randomly chosen turloughs and found that the samples divided into two broad groups. The first group contained all the rendzinas and rendzina-like soils, all the sandy gleys and some river silts of bowl shaped, peat-free turloughs such as those located in Coole-Garryland. The second group consisted of peat soils and peaty alluvial gleys from the shallow, flatter turloughs of the Burren. MacGowran (1985) concluded that the distinction between the two topographically different groups of turloughs was related to variations in the depth and duration of flooding. Coxon (1986) also noted that peat and marl soils were associated with turloughs with a longer duration of flooding while sand/silt and silt/clay mixtures were typical of turloughs that are flooded for a shorter part of the year. Detailed hydrological studies by Tynan *et al.* (2005) have calculated recession constants, which reflect the emptying characteristics of turloughs, for a limited number of sites. Their work to date has shown that epikarstic turloughs, such as those associated with the East Burren, have lower recession constants than mixed-flow system turloughs which indicate slower rates of discharge in the former. Slower rates of discharge or draining result in the turloughs remaining wetter for longer periods which would be expected to influence organic matter decomposition processes. The more organic rich soils associated with the East Burren catchment in contrast to the Coole-Garryland catchment, irrespective of sampling location, suggests that the hydrological conditions induce organic matter accumulation throughout the East Burren turloughs. The low K_t concentrations associated with the East Burren is also thought to be related to the organic nature of the soils and associated parent materials. Histosols (organic soils) are generally low in K (Graham and Fox, 1971) and limestone pavement and marl are low in K bearing minerals such as alkali feldspars, Ca-Na feldspars and micas.

Sahrawat (2004) reviewed the most current literature on organic matter accumulation in wetland soils which summarised several hypotheses to explain such accumulation. These hypotheses included deleterious effects of reduction products such as hydrogen sulphide or volatile fatty acids and toxic concentrations of ammonia, aluminium, iron and other cations in soil solution on microbial activity and the absence of electron acceptors such as iron oxides and hydroxides resulting in retarded organic matter oxidation and mineralization. During the periods of maximum inundation in turloughs these processes would be expected to inhibit organic matter decomposition throughout all of the turloughs under investigation resulting in the generally high soil organic matter contents within both catchments.

The amount of organic matter formed in wetland soils also depends on the amount of organic material added and its humification coefficient defined as the fraction of organic C retained in the soil after one year of decomposition (Wen, 1984). As a general rule, organic material with high lignin contents have high humification coefficients. The botanical origin of the organic material is an important characteristic of organic soil and relatively undecomposed plant remains of sedges and reeds were characteristic of soils from the East Burren. In general plant species from nutrient poor environments, such as *Carex* spp., produce litter that is more difficult to decompose than litter of a species from nutrient rich environments as they generally have higher C:N ratios and higher concentrations of decay resistant compounds (e.g. Berendse *et al.*, 1989; Chapin *et al.*, 1991). The dominance of sedge and reed dominated plant communities in the East Burren would be expected to influence the organic matter decomposition rates and consequent accumulation.

The more alkaline soils associated with the East Burren catchment are most likely linked to the contrasting chemistry of the floodwaters associated with each catchment. The presence of marl substrates in East Burren and their absence from Coole-Garryland are thought to be as a result of the nature of the floodwaters which are dependent on the type of terrain that receives the rainfall and the residence time in the aquifer (Goodwillie, 2001). In turlough areas the groundwater is characteristically hard with an alkalinity of 100-250 mg l^{-1} $CaCO_3$. Where an acid catchment supplies water, as does the Slieve Aughty mountains to Coole-Garryland, the alkalinity stays between 75 and 125 mg l^{-1} $CaCO_3$ (Goodwillie, 2001). The higher alkalinities associated with turloughs in the East Burren would result in higher rates of calcium carbonate deposition (Coxon, 1994) and also the fact that these basins tend to retain floodwater during the summer months is also thought to result in a greater duration of deposition. *Lymnaea* spp. accounted for the majority of snail species forming snail shell marl which are characterised by ecophenotypic life history plasticity which allows them to be highly invasive and adapted to physically unsTable and environmentally unpredicTable habitats (McMahon, 1983) such as turloughs. The vast majority of *Lymnaea* spp. have an annual lifecycle and contribute large volumes of shell marl to turlough substrates on a yearly basis. The wetter nature of turloughs in East Burren is thought to account for the greater amount of shell marl in comparison to Coole-Garryland. The turloughs in Coole-Garryland tend to remain dry throughout the majority of their area during summer months, most likely eliminating *Lymnaea spp.* from all but the lowest elevations. Soils within the East Burren were distinctly more alkaline than the moderately acidic soils in Coole Garryland. Differences in pH status among the two catchments were dependent on sampling location but were less distinct among samples collected from the lower areas of both catchments.

Hawkhill was the only turlough in the Coole Garryland catchment within which snail shell marl was recorded and this was most abundant in the lower areas.

The lack of marl or snail shell marl within Garryland, Caherglassaun and Coole suggests conditions within these turloughs were not conducive to marl deposition and/or shell marl accumulation. During the summer months the lower areas of turloughs located in both catchments tend to remain saturated resulting in pH conditions approaching neutrality (Ponamperuma, 1972).

2.4.2 Variation in nutrient status within and among two contrasting catchment types

Turloughs associated with the two contrasting catchment types were also found to differ in a range of nutrient properties. The results observed for N_t content from both catchments were at the low end of the range of nitrogen levels determined by O`Donovan (1987) in Burren grasslands which ranged between 4 mg g^{-1} DW to 31 mg g^{-1} DW. The trophic sensitivity assessments conducted by NPWS (cf Section 2.2.1) identified the East Burren turloughs as being extremely highly sensitive to enrichment and Coole Garryland turloughs as having a medium sensitivity to enrichment. These assessments indicate that East Burren turloughs have a greater proportion of vegetation types indicative of low N conditions than Coole Garryland. This trophic sensitivity contrast is not reflected in the N_t variations among catchments and may account for this unexpected finding. The importance of organic matter in soil cannot be over emphasised in view of its role in the maintenance of soil fertility and in particular nitrogen fertility (Sahrawat, 2004). The major factors that influence the rate of organic matter formation also determine the mineralization/immobilisation balance of N (Swift *et al.* 1979), thus the accumulation of soil N closely follows that of soil organic matter (Rosswall, 1976). The higher organic matter content associated with the East Burren could account for the higher N_t concentrations in thei catchment. However, ninety-five percent or more of the nitrogen observed in surface soils usually occurs in the organic, unavailable form (Tisdale *et al.* 1990) and information on the plant-available forms of N is required to adequately relate soil N conditions to trophic status (see Chapter 3).

The mean P_t status for both catchments were below the mean reported for Irish grassland soils by Daly *et al.* (2001) (664 mg l^{-1}). The higher P status associated with the Coole Garryland turlough soils (mean 507 mg l^{-1}) in comparison to the East Burren (304 mg l^{-1}) is most likely linked to the nutrient status of the floodwaters arriving to the turloughs and contrasting management practices associated with the catchments. These results reflect the contrasting nutrient sensitivities associated with the two catchments. Phosphorus exists in soils in organic and inorganic forms and 50% or more of the P_t in the A horizon of soils may be present as organic P and the amount depends on the organic matter content of the soil (Kuo, 1991). Al-Abbas and Barber (1964) evaluated the forms of phosphate in a North American catena and found that organic phosphorus showed a wide range of values related to the organic matter content of the soil and that total phosphorus increased as organic matter increased.

Craft and Chiang (2002) report however than waterlogging favours N retention more than P, resulting in preferential accumulation of organic N over P. A high degree of P_{feo} variation was associated with both catchments. The mean P_{feo} concentrations for both catchments were below the mean reported by Daly *et al.* (2001) (23.1 mg l^{-1}). These authors also highlighted that P_{feo} is characterised by a high degree of variation, which was found to range between 3.7 and 75.0 mg l^{-1}. Variations in P_m among the catchments were dependent on sampling location. Interpreting P_m concentations requires accompanying information on whether the associated soils are mineral or peat soils types (Table 2.2). Based on the mean OM contents for each catchment, Coole Garryland soils were considered as mineral soils and East Burren soils were considered as peat soils. The mean P_m status for both catchments reflected a medium P fertility status. East Burren soils are characterised by a high degree of variation in P_m status. If P_m concentrations are interpreted in the absence of soil type data for turloughs they could present a misleading assessment of P fertility status and may not be suiTable for turlough soil nutrient assessments. The P_m extraction method is also pH dependent and may not be suiTable for highly calcareous soils. This may have accounted for the high variations in P_m associated with all sampling locations in the East Burren. The high degrees of variation associated with P_{feo} and P_m emphasise the potential difficulties of quantifying P sorption and desorption dynamics in turlough soils.

Sampling location was found to be an important factor when making comparisons of pH and P_m among turloughs in Coole-Garryland, whereas sampling location was found to influence Ca_t, N_t, P_t, P_{feo} and P_m comparisons among turloughs in the East Burren catchment. Improvements in turlough classification will aid management at a broader level, but individual turlough assessments will be extremely important in order to provide on-going monitoring information, particularly for protected sites. The goal should be to provide individual nutrient assessments in the context of other turloughs and consideration is given here to the implications of spatial variabilty for making comparisons among turloughs with a similar karst typology. It would have been expected that spatial variability would have been a greater issue for making nutrient comparsions among the Coole Garryland turloughs, given their associated undulating topographies. The lower areas of Hawkhill, Caherglassun, Garryland and Coole were associated with greater variations in pH, and variations in Pm among these turloughs was highly dependent on sampling location. These differences in the influence of sampling location on nutrient assessments among the catchments may be linked to contrasting management practices. It seems likely that Coole Garryland turloughs are more intensively grazed than East Burren turloughs and high levels of grazing are likely to influence the natural spatial variability of soil properties by patchy deposition of nutrients throughout the turloughs. The spatial variability observed in East Burren is likely to reflect a more naturally patchy soil nutrient condition.

2.4.3 Variation in nutrient properties within and among common turlough soil types

Gleys and Kilcolgan Series Rendzinas had significantly higher P_t and K_t status than the Fen Peats and Burren Series Rendzinas. These differences in nutrient status reflect the differences in P_t and K_t nutrient status among the catchments. These nutrient differences among the soil types were attributed to the fact that in wetlands, organic soils differ from mineral soils in several physicochemical features such as lower pH, higher bulk density, cation exchange capacity and lower nutrient availability (Mitsch and Gosselink, 2000) as nutrients are generally in organic forms unavailable to plants (Clymo, 1983). MacGowran (1985) also observed differences in nutrient status among organic and mineral turlough soil types and proposed that these differences are potentially linked to the contrasting types and amounts of organic matter content. The main purpose of the soil type comparisons was to assess the implications of within-soil type variation for making nutrient comparisons among soil types for the purposes of understanding turlough vegetation/soil type/hydrology relationships and for soil nutrient assessments. Kilcolgan Series Rendzinas and Gleys were generally associated with upper and lower elevations within Coole Garryland and Burren Series Rendzinas and Fen Peats exhibit a similar elevational distribution within the East Burren catchment. The lack of nutrient differences among the Gleys and Kilcolgan Series Rendzinas and also among the Fen Peats and Burren Series Rendzinas suggests that different flooding durations associated with the upper and lower elevations did not generally promote contrasting P_t or K_t status within either catchment. High degrees of P_{feo} variation were associated with each soil type and Burren Series Rendzinas and Fen Peats were associated with high degrees of P_m variation. These high degrees of variation present challenges for making comparisons of plant available P among turlough soils types and highlight the potentially extremely complex nature of turlough soil sorption and desorption dynamics. Attempts to quantify P dynamics adequately, and to relate them to soil type, would require a large number of samples to take this variation into account. The common soil survey practice of selecting a single soil type profile for nutrient assessment should not be employed in turloughs, particularly for assessments of available-forms of P. It is recommended that a minium of five representative samples from each soil type should be taken in any assessment of turlough soil nutrient status.

2.4.4 Relationships between turlough vegetation types and soil nutrient properties

Three relatively well defined plant communities were identified from the 60 releves using the outlined statistical techniques: cluster analysis, indicator species analysis and ordination. It should ne noted that the cluster analysis provides rather limited support for Goodwillie`s (1992) classification e.g. 5B Potentilla reptans (*spp. poor*) was found in each of the four identified groups. This highlights the need for a quantitative evaluation of the Goodwillie (1992) classification. Both clustering and ordination identified a gradient between grass dominated communities (Groups 1 and 2) and the sedge dominated community (Group 4).

Similarly, O`Connell *et al.* (1984) and Regan *et al.* (2007) demonstrate a broad difference between small sedge dominated swards and more vigorous high nutrient and/or disturbance communities (grass/forb dominated communities). Both the *Ranunculus repens* group (Group 1) and the *Agrostis stolonifera* group (Group 2) were characterised by soils with comparatively low $CaCO_3$ contents, high inorganic contents and organic matter contents indicative of mineral soil types. Gleys and Kilcolgan Series Rendzinas were associated with these vegetation types. Mean P_t, N_t, and K_t concentrations were indicative of a below average, yet moderately enriched soil nutrient status. Both groups were generally associated with a moderately acidic soil conditions. The sedge dominated community was associated with soils with higher $CaCO_3$ and OM contents. The lower inorganic content was indicative of a less mineral soil condition which was reflected in the associated organic, base rich soil types. There was no distinction between the N_t concentrations associated with Groups 1,2 and 4, however Group 4 was associated with markedly lower P_t and K_t concentrations. As cited in Regan *et al.* (2007), small sedge species compete most effectively in areas where water Table levels are relatively constant throughout the season (Gowing and Spoor, 1998). This view is supported by O`Connell *et al.* (1984) who state that small sedge communities are associated with a constantly high water Table and peaty substrates. Findings presented in this thesis suggest that such areas are also associated with more organic, base rich soil types. The observed alkalinity gradient which distinguished Groups 1 and 2 from Group 4 suggests that sedge communities are also associated with alkaline soil conditions, induced by marl deposition and shell marl accumulation, within these wet areas. Goodwillie (1992), Goodwillie *et al.* (1997) and Regan *et al.* (2007) concluded that trophic status is secondary to overall wetness in relation to the distinction between grass/forb dominated communities and sedge dominated communities. The results presented in this thesis suggest that trophic status is also a potentially secondary influence to alkalinity, which is related to overall wetness, in determining the distribution of these vegetation types within and among turloughs.

Goodwillie (2001) states that marl has a major effect on plant life as its high alkalinity and lack of aeration creates specialised conditions for plant roots, favouring species, such as sedge species, tolerant of alkaline conditions. Groups 1 and 2 shared many soil nutrient characteristics. However alkalinity, mineral and K_t gradients explain the subtle distinction between these two vegetation groups. Wide ranges of N_t, P_t and P_{feo} were associated with Groups 1, 2 and 4 which suggests such turlough vegetation communties are well adapted to soils with a patchy, and low soil N and P status.

2.5 Conclusions

The mains findings of work presented in this chapter are:

- Coole Garryland and East Burren differed in a range of nutrient-related properties and in the nature of their soil types. Coole Garryland was characterised by moderately acidic to moderately alkaline, moderately calcareous mineral soils whereas the East Burren was characterised by calcareous, organic soils. Inorganic contents associated with Coole Garryland were higher than within East Burren, independent of sampling location. Variations in pH among the catchments were less distinct at lower elevations, most likely due to increased soil saturation in the lower areas of the Coole Garryland turloughs. The dominant soil types in Coole Garryland were Kilcolgan Series Rendzinas and Gleys whereas Burren Series Rendzinas, Fen Peats, Marls and Peat-marls were characteristic of the East Burren. The differences in the nature of soils among catchments were attributed to the different parent materials, hydrological regimes and hydrochemical conditions associated with the contrasting karst aquifers. These factors were also thought to account for the higher Fe_t, Mg_t and K_t concentrations associated with Coole Garryland and the higher Ca_t concentrations associated with East Burren.

- The general nutrient status of both catchments was low and reflected the high degree of sensitivity to enrichment generally associated with turloughs. P_t and K_t associated with Coole Garryland were higher than the East Burren, independent of sampling location, and reflected the moderate sensitivity versus the extremely high sensitivity to enrichment associated with each of respective catchments. The higher nutrient status of Coole Garryland may be attributed to a combination of interacting factors including the mineral soil types, nutrient enriched floodwaters and possibly more intensive grazing associated with the Coole Garryland turloughs. The low N_t concentrations suggest that that N may be limiting productivity within both catchments.

- Sampling location was found to be an important factor when making comparisons of pH and P_m among turloughs in Coole-Garryland, whereas sampling location was found to influence Ca_t, N_t, P_t, P_{feo} and P_m comparisons among turloughs in the East Burren catchment. This suggests that spatial variability associated with the East Burren turloughs presents a greater challenge for making soil nutrient comparisons among turloughs.

- High degrees of variation were generally associated with the turlough soil types characteristic of each catchment. Gleys and Kilcolgan Series Rendzinas had significantly higher P_t and K_t status than the Fen Peats and Burren Series Rendzinas. Higher degrees of N_t and P_t variation were associated with the Burren Series Rendzinas and Fen Peats than with the Kilcolgan Series Rendzinas and Gleys. Conversely, higher K_t variations were associated with the latter soil types. High degrees of P_{feo} variation were associated with each soil type and Burren Series Rendzinas and Fen Peats were associated with high degrees of P_m variation. These high degrees of variation present challenges for making nutrient comparisons among turlough soils types and potentially for detecting true relationships between soil types, vegetation and hydrology. It is recommended that soil types are described and mapped prior to a turlough soil nutrient survey and a minimum of five representative samples from each soil type should be taken for nutrient assessment.

- Soil nutrient conditions are a potentially secondary influence to alkalinity, which is related to overall wetness, in determining the distribution of grass/forb dominated vegetation communities and sedge dominated communities within and among turloughs.

CHAPTER 3. SPATIAL VARIATIONS OF PLANT-AVAILABLE NUTRIENTS ALONG TURLOUGH FLOODING GRADIENTS

3.1. Introduction

Wetlands are complex systems exhibiting considerable within-site variability (Reddy, 1993), and evidence presented in Chapter 2. suggests that nutrient variations along turlough flooding gradients have implications for comparing nutrient status among catchments and among turloughs within catchments for ecological or monitoring purposes. Detailed studies of the within-site spatial variability of soil properties within wetlands are motivated by a range of different objectives, where the goal is often the refinement of sampling protocols for an accurate spatial description of soil properties or to achieve a thorough understanding of nutrient cycling which takes into account potential spatial patterns. Stolt *et al.* (2001) considered the implications of spatial variability within five wetlands for examining differences in site characteristics and soil morphology among wetlands. Within the wetland sites, elevation trends were observed for particle size and chemical parameters and these elevational trends were related to water Table levels and the depositional environment. Reese and Moorhead (1996) investigated spatial patterns of soil chemical properties along an elevational gradient, with a view to assessing the implications of such spatial patterns for sampling protocol. Significant differences were noted for OC, clay content, CEC, and base saturation for the A horizon across the elevational gradient however the same patterns were not reflected in the B horizon. The authors concluded that the differences in soil parameters in the A horizon may be a reflection of vegetation patterns or hydrology, and sampling protocol for soils of such depressional wetlands may require an evaluation of elevation, hydrology and vegetation patterns to determine spatial patterns of nutrient cycling.

Spatial variability of soil properties is also important to consider when assessing the environmental and ecological functions of a wetland (Stolt *et al.* 2001). Many of these functions such as floodwater storage, traps for sediment, and sinks for various non-point source pollutants are difficult to measure directly. In lieu of direct measurements, particular soil and landscape properties can be recorded and then related to the potential of the wetland to function in one or more of these capacities (Maltby, 1987). The nature of spatial variability within a wetland must be considered to ensure that the full range of such soil, landscape and associated wetness conditions are described. Studies conducted by Johnston *et al.* (1984) on the variations in stratigraphy and distributions of materials in a lakeside wetland aimed to determine what changes in nutrient content occur with depth and with type of depositional material. Phosphorus concentrations were found to be highest in silt/loam alluvium and histic deposits, and lowest in glacio-fluvial deposits, marl and sandy alluvium.

Total phosphorus in the alluvium and glacio-fluvial deposits was very highly correlated with percentage silt and clay. Nitrate concentrations were highest in silt loam alluvium and lowest in saturated histic deposits, indicating that the build up of silt loam alluvium in the wetland has created aerobic soil conditions locally conducive to nitrification. The authors concluded that alluvial deposition is more effective than histic deposit formation for retaining phosphorus in the lakeside wetland and that much of the sediment and nutrient load leaving surrounding upland areas was being trapped in the wetland fringe around the lake, thereby preventing deterioration in lake water quality.

The different capacities of wetland soil types to retain and cycle nutrients are thought to influence plant-nutrient availability. Therefore, different soil types are thought to be an important secondary driver of vegetation ecology in wetlands. Hayati and Proctor (1990) highlighted that much of the variation commonly seen in wet-heath vegetation can be related to variation in the height and seasonal fluctuation of the water Table and associated factors, and to the availability and cycling of the major nutrients N, P and K. These authors conducted a trend surface analysis of spatial variability of soil chemical properties in a sloping wet heath which indicated significant relationships among elevation, vegetation and soil chemical properties across the site. Understanding the factors driving spatial patterns along flooding gradients is fundamental to understanding both the nutrient cycling processes which govern plant-nutrient availability within turloughs and the links between pedological processes and turlough vegetation ecology within catchments.

Previous investigations of the spatial variability of soil properties within turloughs have been conducted in the context of vegetation ecology. Van Ravensburg and van der Wijngaart (2000) investigated the links between vegetation communites and ecological factors of two turloughs Roo West and Roo East in Co. Clare. Within both turloughs there was a high degree of variability in soil N status, ranging from nitrogen poor soils to nitrogen rich soils. Ecological studies conducted by Caffarra (2002) in Coole Lough, Inse woods found that soil attributes showed a marked variability along two transects and results suggested a high degree of variation within a small turlough with a relatively homogeneous vegetation community. Matthijssen (2005) also used transects for investigating the vegetation ecology in two turloughs. Soil properties exhibited very different trends along two spatially distinct contiguous transects in Termon turlough, Co. Galway. For example, OM (% by weight) ranged between 4 and 7 % along one transect and 30-45 % along the other, and common trends in nutrient availability and nutrient pools along both transects were not discernible.

The specific objectives of this chapter are to:

i) compare trends in plant-nutrient availability, and their relationship with soil type and flooding susceptiblity, along the elevation gradient of turloughs within the same catchment,

ii) to provide an assessment of the degree of soil nutrient variability at one point in time within individual turloughs,

iii) to consider the general associations between plant-nutrient availablity and soil physical properties representative of turlough flooding gradients.

3.2 Methods

3.2.1. Sampling along elevation gradients

Caherglassaun and Garryland turloughs (Coole-Garryland catchment) and Cooloorta and Gortlecka (East Burren catchment) were chosen for detailed spatial investigation along the flooding gradients. Access difficulties to Hawkhill and Lough Cuil Reasc prevented further study within these turloughs and the chosen turloughs were selected at random from the other three previously studied sites. One transect was oriented along the flooding gradient in each selected turlough from the upper-most turlough area to the basin floor, as indicated by topographic and vegetation variations. It was considered a priority to ensure that the most common vegetation communities within each turlough were represented along each transect. It was decided to collect a maximum of 16 samples from 4 m^2 quadrats at 3m intervals to a depth of 10 cm using a standard Teagasc (Irish Agriculture and Food Development Authority) corer from each transect due to time constraints. The site of the transect was dictated by the requirement for an area where the vegetation types indicative of upper, middle and lower elevations were included along a distance of 80 m. A 77 m transect was laid out in both Caherglassaun and Garryland. A 52 m and a 42 m transect respectively were laid out in Cooloorta and Gortlecka. 12-15 cores were collected to provide enough soil for the range of analyses. 4 m^2 quadrats were selected as the transects passed through a range of vegetation types from grazed grassland to tall sedge communities and this quadrat size included a representative area of all vegetation types. Samples from each transect were collected over a 2 day period during June 2005. Further description of transect location within each turlough is provided below in Section 3.2.2.

All transects were levelled using differential GPS by personnel from Environmental Engineering, TCD but the elevation data were not made available. It was originally planned to use changes in elevation along the flooding gradients as an indicator of variations in flooding duration. In the absence of this information changes in vegetation were used as an indicator of flooding duration. Variations. It must be stressed that both changes in elevation and vegetation are poor substitute s for hydrological data. As outlined in Section 1.3.3., Tynan *et al.* (2005) and Goodwillie (2003) provide evidence that the depth divisions identified by Goodwillie (1992), based on changes in vegetation communities, provide reliable indicators of decreasing relative elevation and associated flooding susceptibility along topographic gradients in the absence of elevation and hydrological data. Vegetation communities were identifed along each transect using the species dominance within each quadrat, available Goodwillie (1992) maps and indicator species present in the vicinity of each quadrat. Vegetation maps were available for Caherglassaun and Garryland but were not available for Cooloorta and Gortlecka. Each transect was divided into upper, middle and lower zones, the boundaries of which were designated by the depth division of vegetation communities or their associated degree of wetness (Table 1.3, Tables 3.1-3.4).

Where changes in vegetation type were less obvious, changes in species dominance were used to assign areas to elevation zones. For the purposes of this chapter, upper zones were taken as indicating infrequently flooded areas with the shortest annual duration of flooding, lower zones were considered to be frequently flooded and experience the longest duration of annual flooding and middle zones refer to areas experiencing varying degrees of flooding duration. The upper and lower zones along each transect were identified initially as these areas were generally readily identifed. Quadrats lying between these extremes of flooding susceptibility were identified as the middle zone. It is understood that zones within different turloughs experience varying frequencies and durations of flooding but in the absence of integrated elevational and hydrological data this approach was thought to allow for interpretation of soil data in relation to varying degrees of flooding susceptibility. Gravimetric measurements of soil moisture content are of limited usefulness for determining whether a soil is desiccated or saturated. Styles (2004) however described the soil moisture contents associated with 11 common Irish soil associations and found that the gravimetric soil moisture contents ranged between 37-75%. For the purposes of this study, soil moisture contents below 37% were used as an indicator of potential soil desiccation and above 75% as indicative of potential soil saturation.

3.2.2. Sampling site descriptions

3.2.2.1. Garryland

A 77 m transect with a EW orientation was set up along the spur of higher ground in the central basin area (Plate 3.1). Vegetation types occurring along the transect included 2C limestone grassland, 3B Sedge Heath, 6A Dry *C. nigra* and 9B *Eleocharis acicularis*.

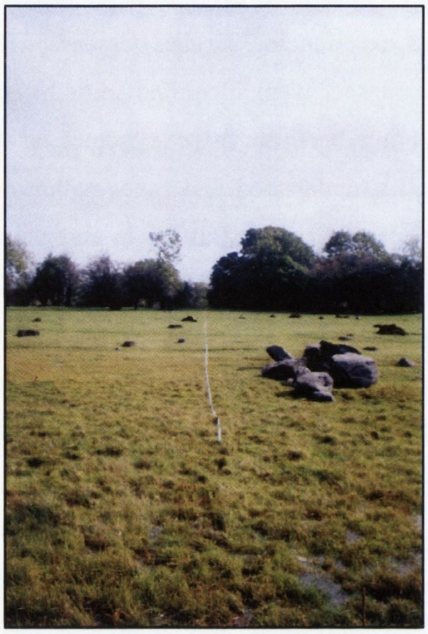

Plate 3.1: 77 m transect along the flooding gradient in Garryland (Coole Garryland) running from the upper infrequently flooded fringe area dominated by *Crataegus monogyna* into the *Carex spp.*-dominated turlough floor area which remains damp and pulses with floodwater during the summer months. Boulders are scattered throughout this turlough.

3.2.2.2. Caherglassaun

A 77m transect (Plate 3.2) with a NS orientation was set up along the northern shore. Vegetation types occurring along the transect included 2B Poor Grassland, 5B *P. reptans* (spp. poor) and 9B *Eleocharis acicularis*.

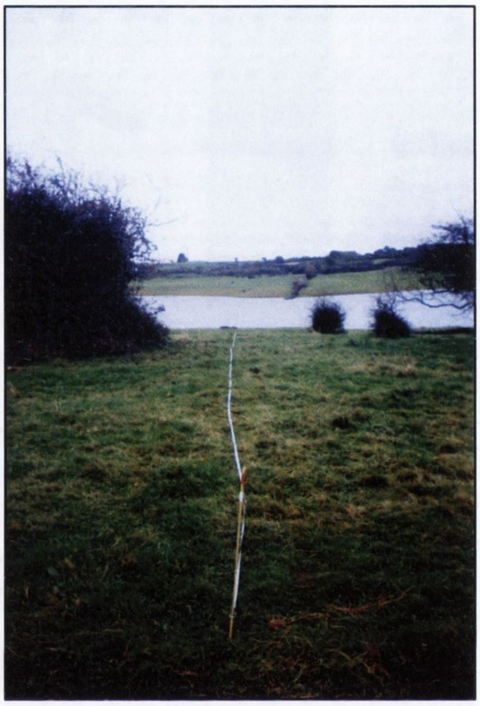

Plate 3.2: 77 m transect along the flooding gradient in Caherglassaun (Coole Garryland) running from the upper fringe dominated by *Crataegus monogyna* into the turlough floor area occupied by a semi-permanent lake.

3.2.2.3 Gortlecka

A 42m transect (Plate 3.3) with a EW orientation was set up along the eastern shore. Vegetation types occurring along the transect included 3W *Rhamnus* Wood and 5D Sedge Fen.

Plate 3.3: 42 m transect along the flooding gradient in Gortlecka, East Burren Catchment running from the upper fringe dominated by *Rhamus* woodland into the *Carex spp.*-dominated turlough floor area.

3.2.2.4. Cooloorta

A 52m transect (Plate 3.4) with an EW orientation was set up along the eastern shore. Vegetation types occurring along the transect included 3B Sedge Heath, 4D Schoenus Fen and 9C Marl Pond.

Plate 3.4: 52 m transect along the flooding gradient in Cooloorta running from the upper fringe dominated by *Calluna vulgaris* into the *Carex elata* dominated turlough floor area.

3.2.3. Soil descriptions

Soil types were described along each transect based on criteria outlined in Section 2.2.5. However, % $CaCO_3$ was not determined on collected soil samples which had previously been used as a diagnostic characteristic for identifying marls and peat- marls. Soil colour, organic matter content and abundance of snail shell marl were therefore used to identify marls and peat-marls.

3.2.4. Laboratory analyses

Samples collected from transects were analysed for pH, OM, SM. Duplicate sub-samples were analysed for plant-available forms of N and P which included nitrate-N (NO_3-N) ammonium-N (NH_4-N), water extracTable P (P_w), oxalate extracTable P (P_{ox}). P_w represents P in the soil solution and P_{ox} represents labile P which can replenish the soil solution P concentration for plant uptake. Samples were also analysed for oxalate extracTable iron (Fe_{ox}) which represents the readily reducible form of Fe. All nutrient analyses were conducted on moist soil samples as studies conducted by Styles *et al.* (2004) on the effect of air-drying soil samples on soil P extraction concluded that air-drying soils significantly increases laboratory P_w values and reduces sample representativeness of variation in P_w between soil types and season. Due to time restrictions, a sub-set of samples from the upper, middle and lower areas of each transect were analysed for total exchangeable bases (TEB) and samples from Cooloorta and Garryland were analysed for N_t and total organic carbon (OC_t). For moist soil analysis, soil samples were sieved through a 4mm brass sieve within three days of collection, and homogenised. The sieved homogenised samples were stored at 4°C in polythene bags prior to analyses which were conducted within one week of sieving. For dry soil analyses, samples were prepared as outlined previously in Section 2.2.6.

Soil Moisture Content (Allen, 1989): 10g of soil were taken from each sieved, homogenised sample, placed into foil trays, weighed and left in an oven at 105°C for 24 hours. The trays were then removed from the oven, allowed to cool and reweighed to calculate moisture loss which was expressed as a percentage.

Water extracTable Phosphorus (P_w) (Van der Pauw, 1971): 40 ml of DDW were added to 125ml polypropylene bottles containing 1g dry-weight equivalent soil (1:40 soil-solution ratio). The bottles were shaken for 30 minutes prior to filtration through 0.45µm Whatman® cellulose-acetate membrane filters and analysed for MRP using the Murphy and Riley (1962) method. Moist soil weights corresponding to oven-dried soil equivalent weights were then calculated for each sample to ensure the correct soil-solution ratio for Pw analyses.

Oxalate-extracTable Phosphorus and Fe (P_{ox} and Fe_{ox}) (Uusitalo and Tuhkanen, 2000): 0.2 M oxalic acid was added to 0.2 M ammonium oxalate (at a ratio of approximately 43% to 57%) to achieve a final pH of 3. 50ml of this solution was added to 125ml polypropylene bottles containing 1g dried soil and shaken at 120 oscillations per minute for 4 hours. The solution was then filtered through Whatman® No. 1 filter paper, diluted in DDW at a ratio of 1:50, and analysed for MRP as outlined below, and for Al and Fe using a Perkin Elmer Atomic Absorption Spectrophotometer. MRP was measured using the method of John (1970). Oxalate extraction is known to dissolve amorphous and poorly crystalline oxides of iron while having little effect on crystalline minerals (McKeague and Day, 1966).

Inorganic (plant-available) Nitrogen (NO_3-N and NH_4-N) (Mulvaney, 1996): 10g of field moist soil was shaken with 2 M KCl for 1hour. The solution was then filtered though Whatman® Cellulose Acetate membrane filters (47mm diameter, 0.45 μm pore size). 10g in 100ml KCl was used as an alternative to 20g in 100ml as the soils generally had a high organic matter content. NO_3^--N was determined spectrophotometrically via air segmented continuous flow analysis using cadmium reduction followed by diazotisation, on a Bran+Luebbe AutoAnalyzer 3 at 550nm wavelength. NH_4^+-N was determined using the Berthelot reaction in which a blue green colour complex is formed which is measured at 660nm. Sodium nitroprusside is used to enhance the sensitivity and a complexing agent is used to prevent the precipitation of Ca and Mg hydroxides. Due to consistent problems with the AutoAnalyser (AA3) and lack of technical assistance, the samples had to be corrected using the mean of the QC values.

Total nitrogen (N_t) and total organic carbon (OC_t) of soil (Verado *et al.*, 1990): Approximately 1 g of dried sample was weighed out into a beaker, the weight recorded, and 5ml DDW plus 5 ml of sulphurous acid added. Additional aliquots of sulphurous acid were added if necessary, until effervescence subsided (this was to `burn off' carbonate C: Verado *et al.*, 1990). The beaker and its contents were then placed on a hot plate overnight for the samples to dry, placed in a desicator to cool, then re-weighed in order to correct for carbonate weight loss in the final expression of OC_t content. Approximately 0.05 to 0.2 g of each sample (depending on approximate OC_t content) was then accurately weighed to 4 decimal places into a small tin cup and loaded into a LECO CNS-1000 elemental analyser. N_t and OC_t were used to calculate C:N ratios for samples collected along the Garryland and Gortlecka flooding gradients.

Total Exchangeable Bases (TEB) (Allen, 1979): Exchangeable cations were determined on acidic/neutral soils using 1M NH_4OAc at pH 7.0 (add 77.1g NH4Oac added to 950 ml deionised water. pH was adjusted to 7.0 with acetic acid or aqueous ammonia and make up to volume). Exchangeable cations were determined on calcareous soils, pH 7.7-8.5, (Finch, 1971) using 1 M NH_4OAc at pH 9.0. 125ml of this solution was then added to 250ml polypropylene bottles containing 5g dry weight equivalent of soil, and shaken at 120 oscillations per minute for one hour. Solutions were filtered through Whatman ® glass-fibre filter papers, diluted at up to 1:200 with DDW and analysed for sodium (Na), potassium (K), calcium (Ca), Magnesium (Mg) using a Perkin-Elmer Atomic Absorption Spectrophotometer.

3.2.5 Data analysis

3.2.5.1. Variation in soil properties along turlough flooding gradients.

Trends in plant nutrient availability within each turlough and their association with soil type and flooding susceptibility were investigated using linear graphs (Figures 3.1-3.4). For each variable, scales were standardised across all graphs, and soil types and zonation (upper, middle and lower) were highlighted to facilitate a visual comparison of trends among turloughs. Coefficients of variation (CV) were calculated for each soil property to provide a relative assessment of variation along each transect. CVs were calculated manually in Microsoft Excel XP using the mean and standard deviation. The CVs of pH values were not computed as the definition of zero is arbitrary for variables expressed as a logarithim i.e. a pH of 0.0 does not mean 'no pH'. Data were transformed to achieve normality using square root for variables with values > 1 and using 1/y for variables with values between 0-1 and >1. The application of a square root to a continuous variable that contains values between 0 and 1 and above 1 is not desirable as the latter set of values become smaller and the former become bigger upon square root transformation.

3.2.5.2. Associations between plant-nutrient availablity and nutrient-related properties.

Organic matter is a key diagnostic characteristic for determining mineral (OM < 20%), organic (OM 20-30%) and peat (>30%) soil types and numerous studies have shown that organic matter content exterts a profound influence on soil nutrient dynamics. Turloughs from both catchments differed in organic matter content and the relationship with plant-nutrient availability is considered in the context of organic matter content as a potential indicator of turlough soil nutrient status. Data from all four turlough flooding gradients were pooled for investigation of the relationships between the plant-available fractions of N and P and soil physico-chemical properties. Investigation of the relationships between soil physico-chemical characteristics and TEB and plant-available forms of K, Mg, Ca were conducted separately on data from the Garryland, Caherglassaun and Gortlecka flooding gradients, as TEB analyses were not conducted on samples from Cooloorta due to an oversight. Relationships between soil physico-chemical characteristics and plant-nutrient availability were investigated using scatterplots and Spearman Rank correlation as the data were non-normal and non-linearly related. Spearman Rank correlation coefficient is a non-parametric rank statistic which measures strength of association between two variables (Lehman and D`Abrera, 1998). Significance testing of the Spearman Rank correlation coefficients was conducted using critical values presented in Zar (1972).

3.3. Results

3.3.1 Variation in soil types and soil type characteristics

Soil type descriptions along each transect are presented in Tables 3.1-3.4. Summary statistics and coefficients of variation for each soil property recorded along each transect are presented in Table 3.5-3.8. Variation patterns of soil property variables along each flooding gradient, and their association with soil type and flooding susceptibility are presented in Figures 3.1-3.4.

3.3.1.1 Caherglassaun

The upper zone of this transect was indicated by Poor Grassland (2B) which is a natural type of fringing grassland occurring at the upper levels of a turlough where there is limited management and naturally damp soils (Goodwillie, 1992) (Table 3.1). Tynan *et al.* (2005) note that this plant community is one that is defined by maximum flood length, and it cannot tolerate being flooded for any greater than 40% (21 weeks approximately) of the year. Very shallow (<30 cm) un-gleyed Rendzinas with sandy loam or sandy clay loam textures and semi-fibrous organic matter occurred in the upper zone.

The middle zone was occupied by the *P. reptans* (spp. poor) (5B) community which is a distinctive community covering large areas of drift-filled turloughs, where superficial drainage is good (Goodwillie, 1992). MacGowran (1985) states however that this community can be flooded for up to 30 weeks and this zone is dominated by Gleys which are distinguished by strong mottling in a brown rather than grey matrix. The deepest soils along the Caherglassaun flooding gradient (in excess of 30 cm) were recorded within this zone (Figure 3.1 a), within which there were both sandy clay loam textures and silty clay loam textures.

The lower elevation was defined by the occurrence of *Eleocharis acicularis* (9B) which is a restricted but distinctive vegetation community in turloughs, and is noted by Goodwillie (1992) as being subject to frequent but intermittent flooding, usually on fine peaty mud. This zone was occupied by shallow, alkaline Gleys and ungleyed Alluvium, both with a silty clay loam texture and semi-fibrous organic matter (Table 3.1).

The lowest degree of soil depth variation (41%, Table 3.5) occurred along this transect and soils of an equally shallow nature occur in the upper and lower zones (Figure 3.1a). The lowest degree of variation in OM (15%, Table 3.5) also occurred along this flooding gradient, which had the narrowest range of OM content ranging between 11.1 and 18.7 % (Table 3.5). Similarly the nature of organic matter was recorded as being consistently semi-fibrous along the flooding gradient (Table 3.1). There was no discernible trend in OM variation with flooding susceptibility (Figure 3.1b). Along this flooding gradient the pH ranged from 5.53 (upper) to 7.87 (lower) (Table 3.5) and pH varied markedly within the Rendzinas and ranged between 5.5 and 7.5 within two adjacent quadrats (Figure 3.1 c). A subtle linear decrease in pH was associated with the Gleys within the middle zone and a distinct increase in pH was associated with the Gley and Alluvial soils in the lower zone, within which highest soil moisture contents relative to the Rendzinas and Gleys were recorded (Figure 3.1d).

3.3.1.2 Garryland

Limestone Grassland (2C) and Sedge Heath (3B) occupied the upper zone of this transect (Table 3.2). Goodwillie (1992) states that Limestone Grassland is stunted, grazed grassland which is frequently found around limestone pavement or on other shallow calcareous soils on turlough margins. Goodwillie also notes that Sedge Heath is usually a short, sheep grazed vegetation on quite level ground near the top edge of a turlough basin. Extremely shallow (≤ 11 cm, Table 3.2) Rendzinas and Gleyed Rendzinas occurred in this upper zone. The rendzinas which occurred within the upper most Limestone Grassland area had a sandy clay loam texture whereas those associated with Sedge Heath had a clay loam texture.

Dry *Carex nigra* (6A) delimited the middle zone (Table 3.2). This community exhibits a wide range of tolerance and is noted by Tynan *et al.* (2005) as being limited by a maximum period of inundation of approximately 43 weeks of the year. Goodwillie (1992) notes that this vegetation community occurs generally towards the base of many turloughs on the margins of long-lasting pools or permanent ponds. The substrate for this community seems generally to be mineral rather than peaty and Goodwillie (1992) notes that some of the purest stands grow on marl and clay. Gleyed rendzinas and Gleys occurred in this zone within which gleying was more prominent than in the upper zone.

The lower section (Table 3.1) was defined by the occurrence of *Eleocharis acicularis* (9B), as in the case of Caherglassaun. The soils associated with this zone, however, were Fen Peats with an organic texture and abundant undecomposed plant material.

There were clear distinctions between soil properties within the upper and lower zones along the Garryland flooding gradient (Figure 3.2 a-d). Rendzinas in the upper level all had extremely shallow soil depths, OM ranging between 10-20 of a semi-fibrous nature, pH ranging between 5.1 and 5.4 and a SM content of approximately 40% The lower level soils all had a soil depth greater than 30cm, and organic matter content greater than 30% of a fibrous nature, pH ranged between 5.8-6.4 and soil moisture content ranged betwee 55-83% indicating saturated conditions. Soil properties within the middle zone varied markedly and a clear distinction between the upper or lower zone was not evident. SD was associated with a CV of 69% (Table 3.5) along this flooding gradient where soils were extremely shallow within the upper zone and steadily increased in depth within the lower zone. OM varied to a greater extent along the flooding gradient in Garryland (36%, Table 3.6) than Caherglassaun (15%, Table 3.5). The soils along the flooding gradient in Garryland were of an acidic nature and the soils ranged from strongly acid (quadrat 1) to slightly acid (quadrat 14) and an increase in pH was associated with the deeper, wetter and more organic rich Gleys and Fen Peats.

3.3.1.3 Gortlecka

The upper region of this transect was clearly distinguished by *Rhamnus* wood (3W) which is characteristic of Burren turloughs where limestone slabs break through the floor or surround the edges of the basin (Goodwillie, 1992). Shallow, alkaline Rendzinas (Burren Series) with an organic texture occurred in the upper zone.

A clear distinction between the middle and lower sections of the transect was not apparent as Sedge Fen 5D dominated the remainder of the transect. This is a characteristic community of highly calcareous turloughs limited by a maximum flooding duration of of 35 weeks per year and associated with peat substrate. The distinction between the upper and middle zones was indicated by *Potentilla fruticosa* which generally occupied infrequently flooded upper zones. The lower zone was distinguished by the dominance of sedge species which indicated a greater degree of habitat wetness. Deeper Rendzinas and a Fen Peat occupied the middle zone, again associated with fibrous organic material. Burren Series Rendzinas also occurred in the lower zone, two of which had prominent gleying (Table 3.3).

The soils were very shallow and were generally below 30 cm (CV 55%). Deeper soils occurred in the middle zone relative to the upper and lower zones (Figure 3.3a). A high degree of OM variation occurred along this flooding gradient (77%) and distinctly higher OM contents were associated with the Fen Peats in the middle zone and Rendzinas in the lower zone relative to the Rendzinas occupying the upper and middle zones (Figure 3.3b). Organic material is consistently fibrous in nature along the flooding gradient and consists of abundant undecomposed plant remains (Table 3.3).

There were no clear relationships between pH or SM variations and flooding susceptibility along the flooding gradient of this turlough. pH ranged from nearly neutral (6.5) to moderately alkaline (7.6). The Rendzinas are all nearly neutral to slightly alkaline whereas a slightly acidic pH is associated with the isolated Fen Peat (Figure 3.3c). Soil moisture ranged between 52 and 71% (Table 3.7) along this flooding gradient and a clear relation with soil type or flooding susceptibility was not evident (Figure 3.3d).

3.3.1.4 Cooloorta

The most defined vegetation zonation occured along the flooding gradient of this turlough. The occurrence of Sedge Heath (3B) dominated by *Calluna vulgaris* defined the upper zone of this transect. The change in vegetation community to *Schoenus* Fen (4D) and the absence of *C. vulgaris* indicated the more frequently flooded middle zone. Organic Rendzinas (Burren Series) occurred in these two zones which were generally associated with abundant snail shell marl (Table 3.4).

The occurrence of Marl Pond dominated by *Carex elata*, *Ranunculus flammula* and *Schoenoplectus lacustris* indicated the lower zone. Marl Pond is part of Group 2 (Table 1.3) which is constrained in its distribution by a minimum flooding duration values and has a flooding tolerance of 5-37 weeks in the year. Deep Peat-marls with abundant snail shell marl, silt textures and semi-fibrous organic material occupied the lower zone (Table 3.4).

The highest degree of variation in soil depth (CV 79%) occurred along this transect. Extremely shallow soils occurred (<20cm) in the upper and middle zones and relatively deeper soils were associated with the lower zone (Figure 3.4a). There was no clear relationship between OM and flooding susceptibility (Figure 3.4b) however soils in the upper and middle zones had abundant undecomposed plant material and the lower zone had organic matter of a semi-fibrous nature (Table 3.4). pH ranged between 7.1 (slightly alkaline) and 8.2 (moderately alkaline) (Figure 3.4c). Clear associations between flooding gradient zonation and abundance of snail shell marl were not evident although the three upper most quadrats lacked snail shell marl (Table 3.4). This was the only transect along which snail shell marl was recorded.

3.3.2 Variation of plant-nutrients in relation to soil type and flooding susceptibility along turlough flooding gradients.

3.3.2.1 Nitrogen

Along the flooding gradient in Caherglassaun the concentrations of NO_3-N and NH_4-N remained very similar to one another and concentrations of both forms of plant-available N remained below 7 mg l^{-1} along the flooding gradient with the exception of quadrat 15, an alluvial soil type in the lower zone, within which a peak of NH_4-N occurred (Figure 3.1e). Disregarding this NH_4-N peak, concentrations of NO_3-N and NH_4-N ranged between 0.01-6.4 mg l^{-1} and 2.5-5.6 mg l^{-1} respectively. NO_3-N (CV 53 %) varied to a greater extent along this flooding gradient than NH_4-N (CV 35 %) (Table 3.5). There was no clear relationship between soil type and/or flooding susceptibility and variations in NO_3-N and NH_4-N along this flooding gradient although it is noteworthy that the peak in NH_4-N concentrations coincided with the alluvial soil in the lower zone with the highest SM content recorded along the flooding gradient. This may suggest an inhibition of nitrification and consequential accumulation of NH_4-N.

Along the Garryland flooding gradient, NH_4-N concentrations remained consistently higher than NO_3-N concentrations with the exception of samples from the Gley soil types in the middle zone where the concentrations converged at an extremely low level (Figure 3.2e). The CVs for both forms of plant-available N were of a similar magnitude, 53% (NO_3-N) and 78% (NH_4-N) (Table 3.6). The majority of soils had NH_4-N concentrations below 10 mg l^{-1} whereas concentrations approaching 30 mg l^{-1} were recorded within a saturated Fen Peat (quadrat 16) in the lower zone (Figure 3.2e) . There was a linear decrease in NO_3-N concentrations with increasing flooding susceptiblity. A relatively lower degree of variation was associated with the N_t concentrations (16%) (Table 3.6) and a sTable linear increase with increasing flooding susceptiblity was apparent with the exception of quadrat 12 which deviated from the general trend (Figure 3.2f). A similarly sTable linear increase in C:N ratios occurred along the Garryland flooding gradient. However, the C:N ratio recorded in the middle zone Rendzina (quadrat 8) deviated from the general trend. The majority of C:N ratios along this flooding gradient ranged between 8.6 and 10.8 whereas the C:N ratio associated with this Rendzina was 6.6 (Figure 3.2g). Within Gortlecka, NH_4-N concentrations remained consistently higher than NO_3-N concentrations along the flooding gradient. Deviation from this trend occurred within the middle zone Fen Peat where the concentrations converged at similarly low levels (Figure 3.3e). NH_4-N concentrations ranged from 3.9-15.1 mg l^{-1} (CV 39%, Table 3.7) whereas a lower range of concentrations, differing by two orders of magnitude and a consequent greater degree of variability, was associated with NO_3-N variations (0.01-4.3 mg l^{-1}) (CV 70%, Table 3.7). The Gortlecka flooding gradient was the only one along which NO_3-N increased with distance along the transect. This turlough did not retain a pool of water within the lower elevations during the summer months. The differences in soil moisture levels as a consequence of this would be expected to result in different rates of N cycling within this turlough in comparison to the other three sites.

Within the Rendzinas on the upper and middle slopes of the Cooloorta flooding gradient, NH_4-N concentrations were higher than NO_3-N concentrations (Figure 3.4e). A change in this trend occurred within the Peat-Marls in the lower zone where concentrations of both forms of plant-available N were of a similarly low magnitude with the exception of the saturated soil within quadrat 10, within which the highest concentrations of NH_4-N were recorded relative to the rest of the transect (Figure 3.4e) . N_t concentrations ranged from 4398-8232 mgl^{-1} (Table 3.8). The majority of samples had N_t concentrations below 6000 mg l^{-1} and highest N_t concentrations (> 6000 mg l^{-1}) were associated with the Peat-Marls (Figure 3.4f). N_t variation was much lower (CV 25%) than variation in NO_3-N (CV 60%) and NH_4-N (CV 49%, Table 3.8). C:N ratios ranged between 8.4 and 15.4 (Table 3.8) along the Cooloorta flooding gradient and the majority were greater than 10 (Figure 3.4g).

3.3.2.2 Phosphorus

Along the flooding gradient in Caherglassaun, P_w concentrations ranged between 0.26 mg l^{-1} (quadrat 5) and 1.33 mg l^{-1} (quadrat 16) and the majority of concentrations were below 1 mg l^{-1} (Table 3.5, Figure 3.1f). There was no clear relationship between P_w variations and soil type or flooding susceptibility, and concentrations of a similar magnitude (> 1 mg l^{-1}) occurred in the upper and lower areas. A contrasting trend in P_{ox} variation occurred along the Caherglassaun flooding gradient where concentrations associated with the upper and middle zones ranged between 51.2 and 101.9 mgl^{-1} and a sharp increase in concentrations (> 400 mg l^{-1}) occurred in the lower zone (Figure 3.1 g).

Along the flooding gradient in Garryland the majority of P_w concentrations associated with the Rendzinas were above 1mg l^{-1} whereas all of the concentrations associated with the Gleys and Fen Peats were below 1mg l^{-1} (Figure 3.2 h). The trend in P_{ox} variation along the Garryland flooding gradient was similar the P_{ox} variation along the Caherglassaun flooding gradient. The majority of concentrations lay within the range 20.3 and 84.2 mgl^{-1} (Figure 3.2 i) and a sharp increases in concentrations (> 200 mg l^{-1}) occurred within the lower zone. Similar CVs were associated with P_{ox} along the Garryland (CV 41 %, Table 3.6) and Caherglassaun (CV 55 %, Table 3.5) flooding gradients.

STable, consistently low P_w concentrations occurred along the flooding gradient in Gortlecka where the majority of concentrations were below 0.5 mg l^{-1} (Figure 3.3 f). No clear relationship between P_w variation and soil type or flooding susceptibility was evident. Within Gortlecka P_{ox} concentrations ranged between 31 and 71.1 mg l^{-1} (Table 3.7). A general decreasing trend in P_{ox} concentrations with increasing flooding susceptibility was evident and the minimum concentration was associated with the Fen Peat (quadrat 6) (Figure 3.3 g).

Similarly to the Gortlecka flooding gradient, P_w concentrations did not exceed 0.5 mg l^{-1} (Figure 3.4 h) along the Cooloorta flooding gradient and ranged between 0.06 and 0.32 mg l^{-1} . There was no clear relationship between P_w variation and soil type or flooding susceptibility. Within Cooloorta extremely low P_{ox} concentrations (< 20 mg l^{-1} , Figure 3.4 i) were associated with the Rendzinas in the upper and middle zones whereas within the peat-marls in the lower zone, concentrations were in excess of 45 mg l^{-1} and reached a maximum of 80 mg l^{-1} (Figure 3.4 i).

3.3.2.3 Fe_{ox}, K_{ex}, Mg_{ex}, Ca_{ex}, TEB

Along the flooding gradient in Caherglassaun, Fe_{ox} concentrations ranged between 3459 and 20568 mg l^{-1}. Samples within the upper and middle zones have Fe_{ox} < 10,000 mg l^{-1} and concentrations in excess of this occur within the lower zone (Figure 3.1 h). K_{ex} ranged between 20 and 139 mg l^{-1} and concentrations decreased with increasing flooding susceptibility (Figure 3.1 i). In contrast, Mg_{ex}, Ca_{ex} and TEB exhibited increasing trends with increasing flooding susceptibility (Figures 3.1 j, k and l respectively) along the flooding gradient.

A general decreasing trend in Fe_{ox} concentrations occurred along the Garryland flooding gradient (Figure 3.2 j) and concentrations ranged between 2796 and 6698 mg l^{-1}. K_{ex} concentrations ranged between 91 and 153 mg l^{-1} and an obvious relationship with variations in flooding susceptibility was not observed (Figure 3.2 k). A greater degree of variation in K_{ex} occurred in Caherglassaun (49 %, Table 3.5) than in Garryland (20 %, Table 3.6). Similarly Mg_{ex} variations lacked a clear relationship with flooding suscpetibility or soil type although highest concentrations were associated with the Fen Peats in the lower turlough area (Figure 3.2 l). Mg_{ex} varied to a similar extent in Caherglassaun (39 %, Table 3.5) and Garryland (45%, Table 3.6). Elevated concentrations of Ca_{ex} and TEB were associated with the lower area of the Garryland transect (Figure 3.2 m and n respectively) in comparison to the upper and lower areas.

Lower ranges of Fe_{ox} concentrations were associated with Gortlecka (612-3122 mg l^{-1}) and Cooloorta (808 – 1734 mg l^{-1}) in comparison to Garryland and Caherglassaun, and there were no obvious relationships with variations in soil type or flooding susceptibility (Figures 3.3 h and Figure 3.4 j). Within Gortlecka higher K_{ex}, Mg_{ex} and Ca_{ex} concentrations were associated with the upper and middle level Rendzinas in comparison to the Fen Peat and lower level Rendzinas (Figures 3.3 i, j, k). There was no clear relationship between TEB and soil type and flooding susceptibility (Figure 3.3 l). Along each flooding, Ca_{ex} was found to be the dominant cation and therefore the variation in Ca_{ex} is closely mirrored by that of TEB along all flooding gradients.

Table 3.1: Soil descriptions, sampling location and associated vegetation types for Caherglassaun. See Section 2.2.5 for corresponding information on soil colour, texture and nature of organic matter. See Appendix C for full plant species names.

Quadrat No.	Transect Distance m	Vegetation Zone	Colour	Texture	Organic Matter	Soil Depth cm	pH	%OM	Soil type	Broad soil group	Species
1	0-2	Poor grassland 2B Upper	Brown (10 YR 4/3)	Sandy loam	Semi-fibrous	18	6.3	12.8	Rendzina, KS	Rendzina	*F. rubra, M. caerulea, B. perennis, F. ulmaria, P. lanceolata, R. repens, R. crispus, T. repens.*
2	5-7	Poor grassland 2B Upper	Brown (10 YR 4/4)	Sandy loam	Semi-fibrous	10	5.5	13.4	Rendzina, KS	Rendzina	*F. rubra, M. caerulea, P. arundinacea,*
3	10-12	Poor grassland 2B Upper	Brown (10 YR 4/3)	Sandy loam	Semi-fibrous	22	7.5	17.6	Rendzina, KS	Rendzina	*F. rubra, P. annua,B. perennia, F. ulmaria, P. lanceolata, P. reptans, R. repens, R. crispus,*
4	15-17	Poor grassland 2B Upper	Brown (10 YR 4/4)	Sandy clay loam	Semi-fibrous	27	6.1	12.2	Rendzina, KS	Rendzina	*F. rubra, P. annua, P. arundinacea*
5	20-22	Poor grassland 2B Upper	Dark brown (10 YR 3/.3)	Sandy clay loam	Semi-fibrous	15	7.2	18.1	Rendzina, KS	Rendzina	*F. rubra, P. annua, L. corniculatus, P. lanceolata, P. anserina, T. repens.*
6	25-27	*P. reptans* (spp. poor) 5B Middle	Dark brown (10 YR 3/3)	Sandy clay loam	Semi-fibrous	16	6.7	15.5	Rendzina, KS	Rendzina	*Carex spp., P. annua, F. ulmaria, L. autumnale, L. corniculatus, P. lanceoolata, P. anserina, R. repens, T. repens.,*
7	30-32	*P. reptans* (spp. poor) 5B Middle	Dark brown (10 3/3) with dark yellowish brown mottles (10 4/6). Extremely fine, distinct, sharp, many.	Sandy clay loam	Semi-fibrous	23	6.6	16.8	Gley	Gley	*Carex spp., P. annua, F. ulmaria, L. aumtumnale, L. corniculatus, P. lanceolata, P. anserina, P. reptans, R. repens, T. repens.*
8	35-37	*P. reptans* (spp. poor) 5B Middle	Dark brown (10 3/3) with dark yellowish brown mottles (10 4/6). Extremely fine, distinct, sharp, many.	Sandy clay loam	Semi-fibrous	27	6.7	14.3	Gley	Gley	*Carex spp., P. annua, P. arundinacea,*
9	40-42	*P. reptans* (spp. poor) 5B Middle	Brown (10 YR 4/3) with dark yellowish brown mottles (10 YR 4/6). Extremely fine, distinct, sharp,	Sandy clay loam	Semi-fibrous	32	6.6	16.5	Gley	Gley	*A. stolonifera, P. annua, Carex spp., F. ulmaria, L. autumnale, L. corniculatus, P. anserina, P. reptans, T. repens.*

			many.								
10	45-47	*P. reptans* (spp. poor) 5B Middle	Brown (10 YR 4/3) with dark yellowish brown mottles (10 YR 4/6). Extremely fine, distinct, sharp, many.	Sandy clay loam	Semi-fibrous	46	6.2	15.9	Gley	Gley	*A. stolonifera, P. annua, Carex spp., F. ulmaria, L. corniculatus, P. anserina, P. reptans, R. repens, T. repens.*
11	50-52	*P. reptans* (spp. poor) 5B Middle	Brown (10 YR 4/3) with dark yellowish brown mottles (10 4/6). Extremely fine, distinct, sharp, many.	Silty clay loam	Semi-fibrous	41	6.2	14.1	Gley	Gley	*A. stolonifera, P. annua, Carex spp., P. anserina, P. reptans, R. repens, T. rpens.*
12	55-57	*P. reptans* (spp. poor) 5B Middle	Brown (10YR 4/3) with yellowish brown mottles (10 YR 5/8). Very fine, distinct, clear, common.	Silty clay loam	Semi-fibrous	37	5.9	13.6	Gley	Gley	*Carex spp., P. annua, P. anserina, P. reptans, R. repsns, T. repens.*
13	60-62	*P. reptans* (spp. poor) 5B Middle	Brown (10YR 4/3) with dark yellowish brown mottles (10 YR 4/6). Very fine, distinct, clear, common.	Silty clay loam	Semi-fibrous	39	6.2	18.7	Gley	Gley	*A. stolonifera, Carex spp., E. palustris, M. aquatica, P. anserina, R. repens,*
14	65-57	*Eleocharis acicularis* 9B Lower	Brown (10 YR 4/3) with dark yellowish brown mottles (10 YR 4/6). Very fine, distinct, clear, common.	Silty clay loam	Semi-fibrous	24	7.9	11.0	Gley	Gley	*A. stolonifera, E. palustris, L. uniflora.*
15	70-72	*Eleocharis acicularis* 9B Lower	Dark brown (10 YR 3/3)	Silty clay loam	Semi-fibrous	17	7.1	14.2	Alluvium	Alluvium	*L. uniflora*
16	75-77	*Eleocharis acicularis* 9B Lower	Dark brown (10 YR 3/3)	Silty clay loam	Semi-fibrous	19	7.4	14.3	Alluvium	Alluvium	*L. uniflora*

Table 3.2: Soil descriptions, sampling location and associated vegetation types for Garryland. See Section 2.2.5 for corresponding information on soil colour, texture and nature of organic matter. See Appendix C for full plant species names.

Quadrat No.	Transect Distance m	Vegetation Zone (Location)	Colour	Texture	Organic Matter	Soil Depth cm	pH	%OM	Soil type	Broad soil group	Species
1	0-2	Limestone grassland 2C Upper	Dark yellowish brown (10 YR 3/4)	Sandy clay loam	Semi-fibrous	9	5.1	13.9	Rendzina, KS	Rendzina	*A. stolonifera, F. rubra, L. corniculatus, P. anserina, T. repens.*
2	5-7	Limestone grassland 2C Upper	Dark yellowish brown (10 YR 3/4)	Sandy clay loam	Semi-fibrous	10	5.2	14.8	Rendzina, KS	Rendzina	*A. stolonifera, F. rubra,L. autumnale, P. anserina, T. repens.*
3	10-12	Sedge Heath 3B Upper	Brown (10 YR 4/3)	Clay loam	Semi-fibrous	9	5.1	14.9	Rendzina, KS	Rendzina	*A. stolonifera, Carex spp., L. autumnale, L. corniculatus, T. repens.*
4	15-17	Sedge Heath 3B Upper	Brown (10 YR 4/3)	Clay loam	Semi-fibrous	10	5.3	15.6	Rendzina,KS	Rendzina	*A. stolonifera, Carex spp., L. autumnale, L. corniculatus, T. repens.*
5	20-22	Sedge Heath 3B Upper	Brown (10 YR 4/3) with yellowish brown mottles (10 YR 5/6). Extremely fine, feint, sharp, common.	Clay loam	Semi-fibrous	9	5.2	16.3	Gleyed Rendzina, KS	Rendzina	*A stolonifera, Carex spp., L. corniculatus, P. anserina, T. repens.*
6	25-27	Sedge Heath 3B Upper	Brown (10 YR 4/3) with yellowish brown mottles (10YR 5/8). Very fine, distinct, clear, common.	Clay loam	Semi-fibrous	11	5.2	16.7	Gleyed Rendzina, KS	Rendzina	*A. stolonifera, Carex spp., L. autumnale, L. corniculatus, P. anserina, T. repens.*
7	30-32	Sedge Heath 3B Upper	Brown (10 YR 4/3) with brownish yellow mottles (10 YR 6/8). Very fine, distinct, sharp, many.	Clay loam	Semi-fibrous	9	5.4	19.0	Gleyed Rendzina,KS	Rendzina	*A stolonifera, Carex spp., L. autumnale, L. corniculatus, T. repens.*
8	35-37	Dry *Carex nigra* 6A Middle	Greenish grey (Gley 1 5/1) with brownish yellow mottles (10YR 6/8). Fine, prominent, diffuse,	Clay loam	Semi-fibrous	10	5.4	19.8	Gleyed Rendzina,KS	Rendzina	*A. stolonifera, P. arundinacea, Carex spp., L. corniculatus, P. anserina.*

			many.								
9	40-42	Dry *Carex nigra* 6A Middle	Greenish grey (Gley 1 5/1) with brownish yellow mottles (10 YR 6/8). Fine, prominent, diffuse, many.	Silty clay loam	Semi-fibrous	11	5.8	21.5	Gleyed Rendzina,KS	Rendzina	*A. stolonifera, P. arundinaceae, Carex spp. L. corniculatus, P. anserina, R. repens.*
10	45-47	Dry *Carex nigra* 6A Middle	Greenish grey (Gley 1 5/1) with brownish yellow mottles (10 YR 6/8). Fine, prominent, diffuse, many.	Silty clay loam	Semi-fibrous	22	6.3	24.8	Gley	Gley	*Carex spp., A stolonifera, P. arundinacea, P. anserina, R. repens.*
11	50-52	Dry *Carex nigra* 6A Middle	Greenish grey (Gley 1 5/1) with brownish yellow mottles (10 YR 6/8). Fine, prominent, diffuse, many.	Silty clay	Semi-fibrous	25	6.1	20.9	Gley	Gley	*A. stolonifera, Carex spp., E. palustris, P. anserina, R. repens.*
12	55-57	*Eleocharis acicularis* 9B Lower	Dark brown (10YR 3/3)	Organic	Fibrous	31	5.8	36.9	Fen Peat	Fen Peat	*Carex spp., E. acicularis, E. palustris, Equisetum fluvitale,*
13	60-62	*Eleocharis acicularis* 9B Lower	Dark brown (10YR 3/3)	Organic	Fibrous	35	6.4	34.2	Fen Peat	Fen Peat	*Carex spp., E. acicularis, E. palustris, Equisetum fluvitale,*
14	65-57	*Eleocharis acicularis* 9B Lower	Dark brown (10 YR 3/3)	Organic	Fibrous	40	6.1	33.1	Fen Peat	Fen Peat	*Carex spp., E. acicularis, E. palustris, Equisetum fluvitale,*
15	70-72	*Eleocharis acicularis* 9B Lower	Dark brown (10YR 3/3)	Organic	Fibrous	45	6.2	26.1	Fen Peat	Fen Peat	*Carex spp., E. acicularis, E. palustris, Equisetum fluvitale,*
16	75-77	*Eleocharis acicularis* 9B Lower	Very dark grey (10 YR 3/1)	Organic	Fibrous	47	6.4	37.4	Fen Peat	Fen Peat	*Carex spp., E. acicularis, E. palustris, E. fluvitale, G. palustre, R. flammula.*

Table 3.3: Soil descriptions, sampling location and associated vegetation types for Gortlecka. See Section 2.2.5 for corresponding information on soil colour, texture and nature of organic matter. See Appendix C for full plant species names.

Quadrat No.	Transect Distance m	Vegetation Zone	Colour	Texture	Organic Matter	Soil Depth cm	pH	%OM	Soil type	Broad soil group	Species
1	0-2	*Rhamnus* wood 3W Upper	Dark brown (10 YR 3/3)	Organic	Fibrous	8	7.4	7.6	Rendzina, BS	Rendzina	*M. caerulea, Carex spp., G. boreals, L. corniculatus, P. fruticosa, R. fruticosa, T. repens.*
2	5-7	*Rhamnus* wood 3W Upper	Dark brown (10 YR 3/3)	Organic	Fibrous	8	7.6	7.5	Rendzina, BS	Rendzina	*M. caerulea, Carex spp., L. corniculatus, P. erecta, P. fruticosa, S. repens.*
3	10-12	*Rhamnus* wood 3W Upper	Dark brown (10 YR 3/3)	Organic	Fibrous	11	7.2	7.4	Rendzina, BS	Rendzina	*M. caerulea, Carex spp.,G. boreale, L. autumnale, L. corniculatus, P. anserina, P. fruticosa, S. repens.*
4	15-17	Sedge Fen 5D Middle	Very dark brown (10 YR 2/2)	Organic	Fibrous	31	6.9	7.6	Rendzina, BS	Rendzina	*Carex spp., G. palustre, L. autumnale, L. corniculatus, P. anserina, P. erecta, R. repens.*
5	20-22	Sedge Fen 5D Middle	Very dark grey (10 YR 3/1)	Organic	Fibrous	30	6.8	8.4	Rendzina, BS	Rendzina	*P. australis, Carex spp., L. autumnale, L. corniculatus, M. arvensis, P. anserina, R. repens, S. repens.*
6	25-27	Sedge Fen 5D Middle	Very dark grey (10 YR 3/1)	Organic	Fibrous	40	6.5	40.7	Fen Peat	Fen Peat	*M. caerulea, Carex spp., P. anserina, P. erecta, R. repens, S. repens.,*
7	30-32	Sedge Fen 5D Lower	Very dark grey (10 YR 3/1)	Organic	Fibrous	16	6.8	38.0	Rendzina, BS	Rendzina	*Carex spp.., L. autumnale, L. corniculatus, M. arvensis, P. anserina, R. repens.*
8	35-37	Sedge Fen 5D Lower	Pinkish grey (7.5 YR 6/2) with reddish yellow mottles (7.5 YR 7/8). Very fine, distinct, clear, common.	Organic	Fibrous	20	7.0	36.4	Rendzina, BS	Rendzina	*Carex spp., L. autumnale, L. corniculatus, P. anserina, R. repsns.*
9	40-42	Sedge Fen 5D Lower	Very dark grey (10YR 3/1) with brownish yellow mottles (10 YR 6/6). Very fine, distinct, clear, common.	Organic	Fibrous	19	6.9	40.9	Rendzina, BS	Rendzina	*Carex spp., L. autumnale, M. arvensis, P. anserina, R. repens, S. repens.*

Table 3.4: Soil descriptions, sampling location and associated vegetation types for Cooloorta. See Section 2.2.5 for corresponding information on soil colour, texture and nature of organic matter. See Appendix C for full plant species names.

Quadrat No.	Transect Distance m	Vegetation Zone	Colour	Texture	OM	Soil Depth cm	pH	%OM	Soil type	Broad soil group	Species
1	0-2	Sedge Heath 3B Upper	Dark brown (10 YR 3/3)	Organic	Fibrous	5	7.7	26.1	Organic Rendzina BS	Rendzina	*M. caerulea, C. vulgaris, C. dissectum, P. erecta, S. nigricans.*
2	5-7	Sedge Heath 3B Upper	Dark brown (10 YR 3/3)	Organic	Fibrous	15	7.9	24.6	Organic Rendzina BS	Rendzina	*M. caerulea, C. vulgaris, C. dissectum, L. corniculatus, P. maritima, P. erecta, P. reptans, P. vulgaris, S. nigricans, S. pratensis.*
3	10-12	Sedge Heath 3B Upper	Dark brown (10 YR 3/3)	Organic	Fibrous	14	7.7	23.1	Organic Rendzina BS	Rendzina	*M. caerulea, C. vulgaris, C. dissectum, L. corniculatus, P. maritima, P. erecta, P. vulgaris, S. repens, S. nigricans, S. pratensis.*
4	15-17	Sedge Heath 3B Upper	Dark brown (10 YR 3/3). Abundant, very fine flecks of snail shell marl (10 YR 8/1 white).	Organic	Fibrous	11	7.1	34.7	Organic Rendzina BS	Rendzina	*M. caerulea, C. vulgaris, C. dissectum, L. corniculatus, P. maritima, P. erecta, P. vulgaris, S. repens, S. nigricans, S. pratensis.*
5	20-22	Sedge Heath 3B Upper	Dark brown (10 YR 3/3) Abundant, very fine flecks of snail shell marl (10 YR 8/1 white).	Organic	Fibrous	15	7.6	33.8	Organic Rendzina BS	Rendzina	*M. caerulea, C. vulgaris, P. maritima, P. erecta, P. vulgaris, S. repens, S. nigricans, S. pratensis.*
6	25-27	*Schoenus* Fen 4D Middle	Dark brown (10 YR 3/3). Abundant, very fine flecks of snail shell marl (10 YR 8/1 white).	Organic	Fibrous	16	7.9	32.4	Organic Rendzina BS	Rendzina	*M. caerulea, P. arundinacea, P. erecta, S. nigricans,*
7	30-32	*Schoenus* Fen 4D Middle	Dark brown (10 YR 3/3) Abundant, very fine flecks of snail shell marl, (10 YR 8/1 white).	Organic	Fibrous	8	8.2	24.8	Organic Rendzina BS	Rendzina	*M. caerulea, P. erecta, S. repens, S. nigricans.*
8	35-37	Marl pond 9C Lower	Black (10 YR 2/1). Abundant, very fine flecks of snail shell marl (10 YR 8/1)	Silt	Semi-fibrous	25	7.7	46.3	Peat-marl	Peat-marl	*J. bulbosus, R. flammula*

9	40-42	Marl pond 9C Lower	Black (10 YR 2/1). Abundant, veryfine flecks of snail shell marl (10 8/1 white).	Silt	Semi-fibrous	50	7.7	43.6	Peat-marl	Peat-marl	*C. elata, B. ranunculoides, J. bulbosus, M. aquatica, R. flammula, S. lacustris*
10	45-47	Marl pond 9C Lower	Dark brown (10 YR 3/3) Abundant, very fine flecks of snail shell marl (10 YR 8/1 white).	Silt	Semi-fibrous	51	7.4	28.2	Peat-marl	Peat-marl	*C.elata, B. ranunculoides, J. bulbosus, L. uniflora, M. spicatum, R. flammula, S. lacustris.*
11	50-52	Marl pond 9C Lower	Dark brown (10 YR 3/3). Abundant, very fine flecks of snail shell marl (7.5 YR 8/1 white).	Silt	Semi-fibrous	53	7.4	20.7	Peat-marl	Peat-marl	*B. ranunculoides, L. uniflora, M. spicatum, P. natans, R. flammula, S. lacustris*

Table 3.5: Summary statistics and variation in soil properties along the flooding gradient in Caherglassaun (n=16) and K_{ex}, Ca_{ex}, Mg_{ex}, TEB (n=9). Coefficients of variation (CV) were calculated on transformed data.

	pH	%SM	%OM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}	P_{ox} mg l^{-1}	K_{ex} mg l^{-1}	Mg_{ex} mg l^{-1}	Fe_{ox} mg l^{-1}	Ca_{ex} mg l^{-1}	TEB meq
Mean	6.6	42	14.9	3.9	5.5	9.4	0.7	212	92	112	7493	3530	28
SD	0.6	7	2.2	2.03	5.7	5.2	0.3	299	45	95	5762	1539	12
Min	5.5	36	11.1	0.01	2.5	3.8	0.3	51	20	42	3459	1558	12
Max	7.9	62	18.7	6.4	26.5	26.5	1.3	1045	139	328	20568	6078	48
CV	N/A	17	15	53	35	26	46	55	49	39	34	44	43

Table 3.6: Summary statistics and variation in soil properties along the flooding gradient in Garryland (n=16) and K_{ex}, Ca_{ex}, Mg_{ex}, TEB (n=9). Coefficients of variation (CV) were calculated on transformed data.

	pH	%SM	%OM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	N_t mg l^{-1}	P_w mg l^{-1}	P_{ox} mg l^{-1}	K_{ex} mg l^{-1}	Mg_{ex} mg l^{-1}	Fe_{ox} mg l^{-1}	Ca_{ex} mg l^{-1}	TEB meq
Mean	5.7	52	23	2.6	8.3	10.9	5366	0.8	50.6	113	79	4382	2327	25
SD	0.5	15	8.3	1.5	6.5	7.02	868	0.53	52.2	22	35	1315	1731	21
Min	5.1	40	14	0.01	0.5	1.7	4024	0.17	20.3	91	40	2796	851	8
Max	6.4	83	37	5.0	27.4	29.4	6765	1.76	237	153	153	6698	4748	59
CV	N/A	29	36	57	78	33	16	66.4	41	20	45	30.01	74.4	82

Table 3.7: Summary statistics and variation in soil properties along the flooding gradient in Gortlecka (n=9). Coefficients of variation (CV) were calculated on transformed data.

	pH	%SM	%OM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}	P_{ox} mg l^{-1}	K_{ex} mg l^{-1}	Mg_{ex} mg l^{-1}	Fe_{ox} mg l^{-1}	Ca_{ex} mg l^{-1}	TEB meq
Mean	7	59	22	2.1	9.8	11.9	0.3	55.5	189	95	1905	9138	72
SD	0.3	6	17	1.5	3.8	3.7	0.2	13.3	63	44	949	4161	14
Min	6.5	52	7.4	0.01	3.9	6.5	0.2	31	111	52	612	4502	60
Max	7.6	71	41	4.3	15.1	17.2	0.7	71.1	295	177	3122	16369	97
CV	N/A	11	77	70	39	31	54	24	33	46	50	46	19

Table 3.8: Summary statistics and variation in soil properties along the flooding gradient in Cooloorta (n=11). Coefficients of variation (CV) were calculated on transformed data.

	pH	%SM	%OM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	N_t mg l^{-1}	P_w mg l^{-1}	P_{ox} mg l^{-1}	Fe_{ox} mg l^{-1}
Mean	7.6	56	31	1.1	7.9	9.0	5480	0.2	31.1	1271
SD	0.3	16	8.4	0.7	3.8	3.6	1351	0.07	27.7	264
Min	7.1	40	21	0.3	1.8	2.7	4398	0.06	6.9	808
Max	8.2	80	46	2.8	13.0	13.7	8232	0.3	84.5	1734
CV	4	28	27	60	49	40	25	46	89	21

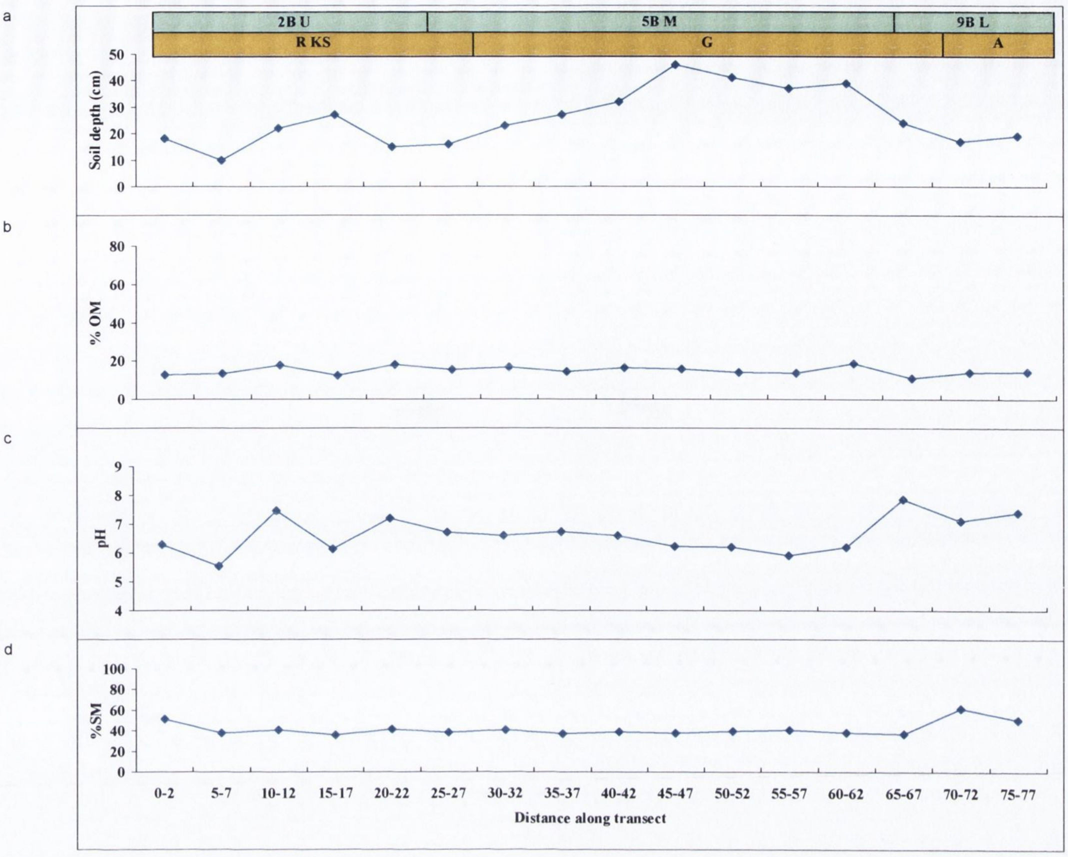

Figure 3.1: Variation in a) Soil depth; b) OM; c) pH and d) SM along the flooding gradient in Caherglassaun. OM values are the mean of duplicate sub-samples. Green bars indicate vegetation; 2B U = Poor Grassland (upper); 5B M = *P. reptans* (spp. poor) (middle); 9B L = *Eleocharis acicularis* (lower). Brown bars indicate soil type; R=Rendzina; G = Gley; A = Alluvium.

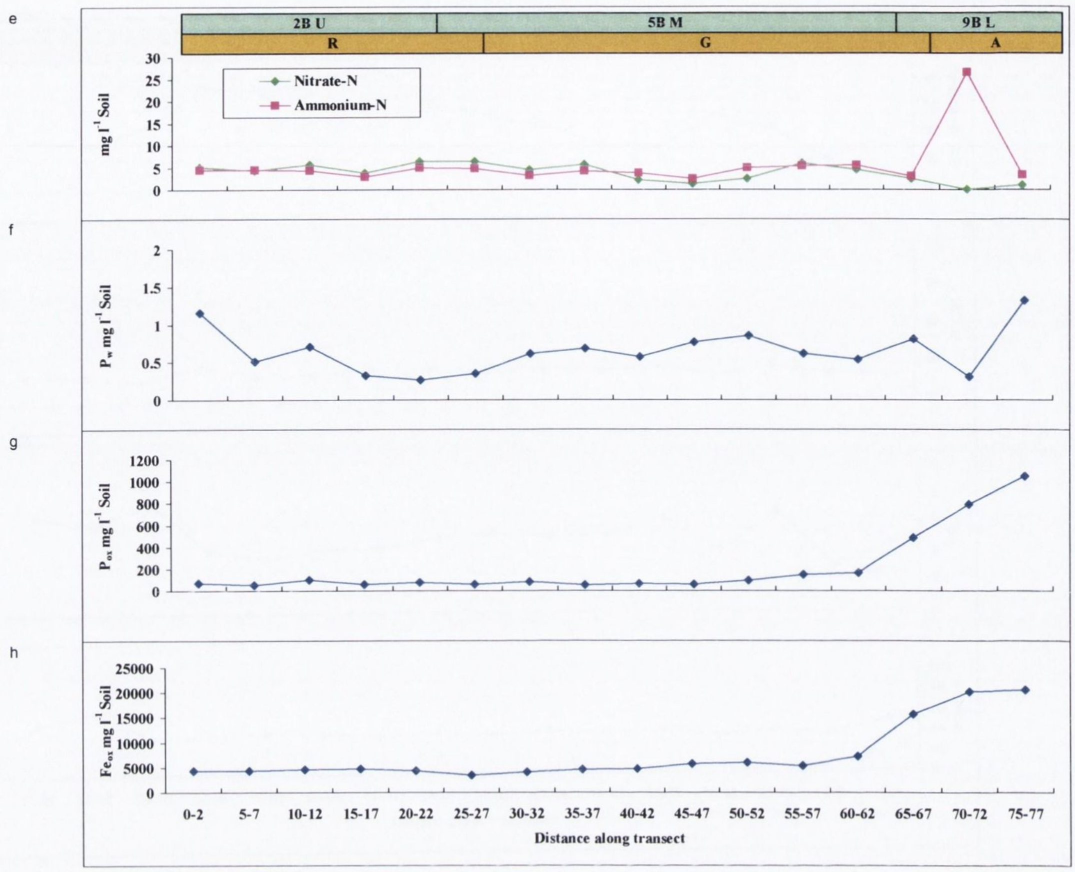

Figure 3.1: Variation in e) NO_3-N and NH_4-N; f) P_w; g) P_{ox} and h) Fe_{ox} along the flooding gradient in Caherglassaun. Values are the mean of duplicate sub-samples. Green bars indicate vegetation along transect; 2B U = Poor Grassland (upper); 5B M = *P. reptans* (spp. poor) (middle); 9B L = *Eleocharis acicularis* (lower). Brown bars indicate soil type along the transect; R=Rendzina; G = Gley; A = Alluvium.

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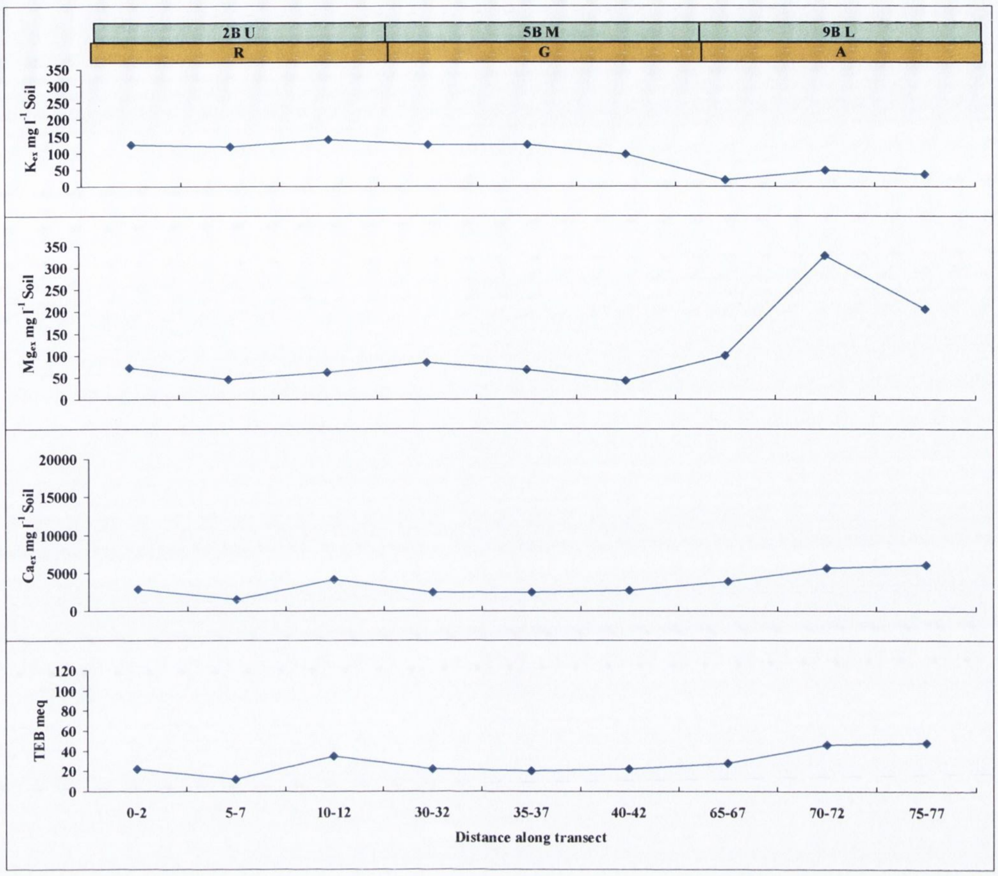

Figure 3.1: Variation in h) K_{ex}; i) Mg_{ex}; j) Ca_{ex} and k) TEB along the flooding gradient in Caherglassaun. Values are the mean of duplicate sub-samples. Green bars indicate vegetation; 2B U = Poor Grassland (upper); 5B M = *P. reptans* (spp. poor) (middle); 9B L = *Eleocharis acicularis* (lower). Brown bars indicate soil type; R=Rendzina; G = Gley; A = Alluvium.

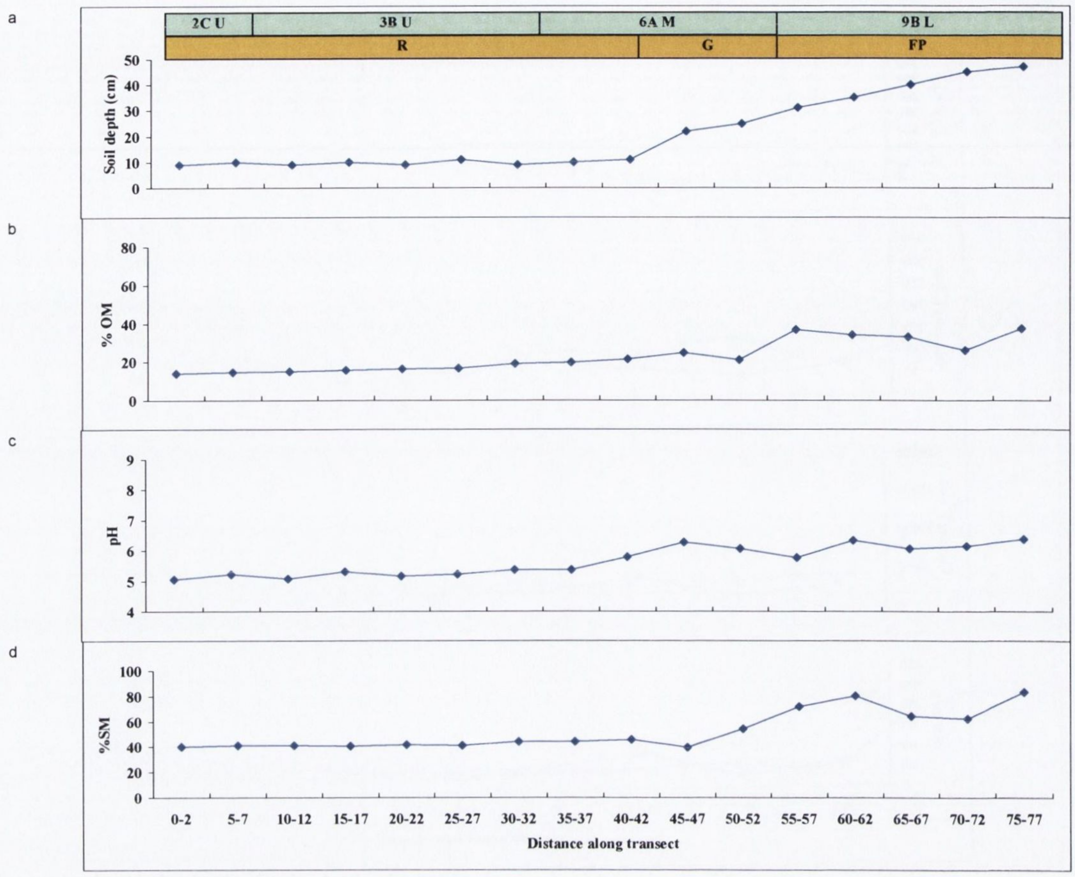

Figure 3.2: Variation in a) Soil depth; b) OM; c) pH and d) SM along the flooding gradient in Garryland. OM values are the mean of duplicate sub-samples. Green bars indicate vegetation; 2C U = Limestone Grassland (upper); 3B U = Sedge Heath (upper); 6A M = Dry *Carex nigra* (middle) and 9B L = *Eleocharis acicularis* (lower). Brown bars indicate soil type; R=Rendzina; G = Gley; FP = Fen Peat.

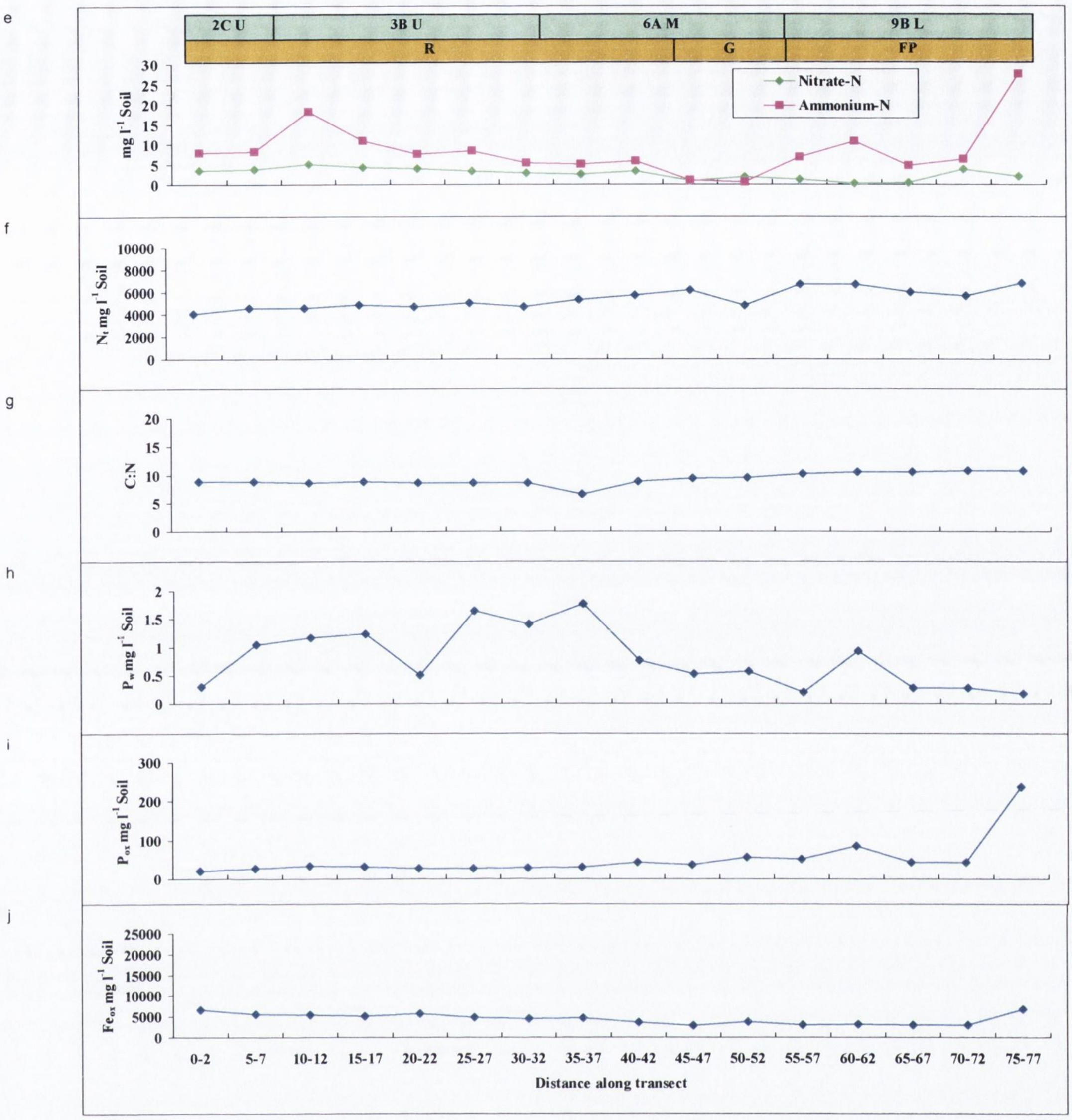

Figure 3.2: Variation in e) NO_3-N and NH_4-N; f) N_t; g) C:N; h) P_w; i) P_{ox}; j) Fe_{ox} along the flooding gradient in Garryland. Values are the mean of duplicate sub-samples. Green bars indicate vegetation; 2C U = Limestone Grassland (upper); 3B U = *Sedge Heath* (upper); 6A M = Dry *Carex nigra* (middle) and 9B L = *Eleocharis acicularis* (lower). Brown bars indicate soil type; R=Rendzina; G = Gley; FP = Fen Peat.

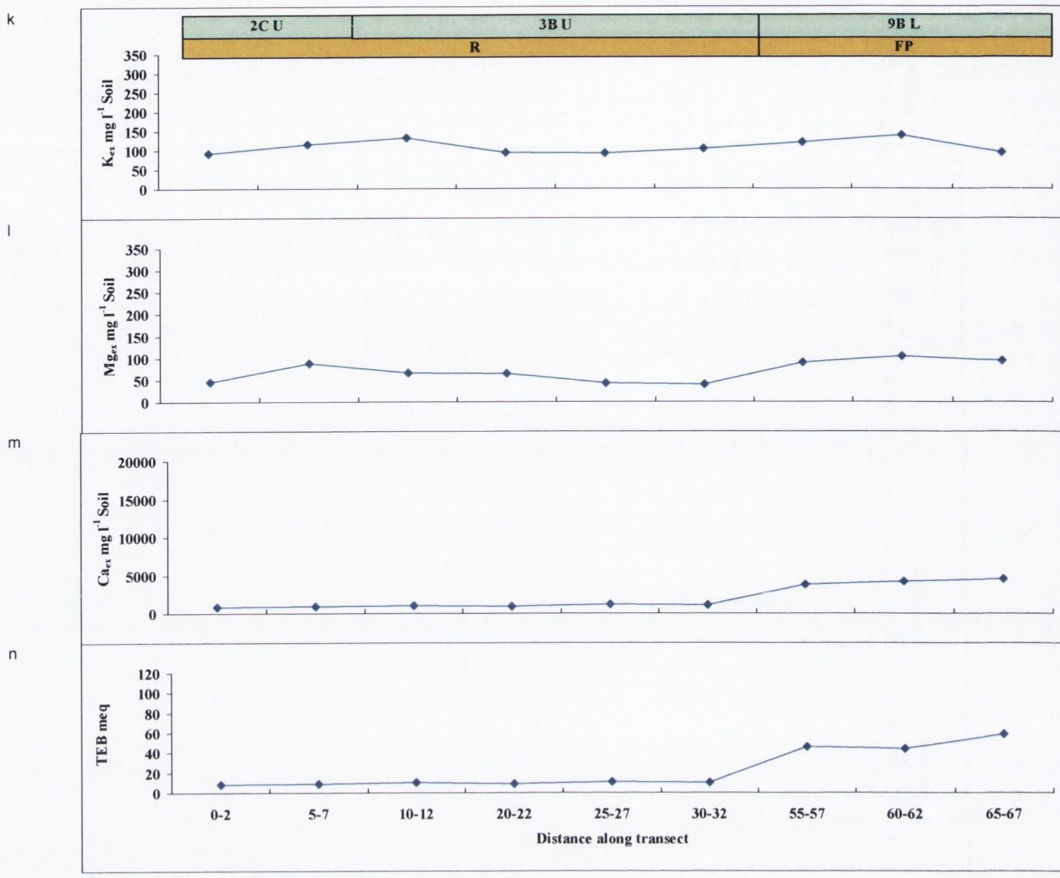

Figure 3.2: Variation in k) K_{ex}; l) Mg_{ex}; m) Ca_{ex} and n) TEB along the flooding gradient in Garryland. Values are the mean of duplicate sub-samples. Green bars indicate vegetation; 2C U = Limestone Grassland (upper); 3B U = Sedge Heath (upper); 6A M = Dry *Carex nigra* (middle) and 9B L = *Eleocharis acicularis* (lower). Brown bars indicate soil type; R=Rendzina; G = Gley; FP = Fen Peat.

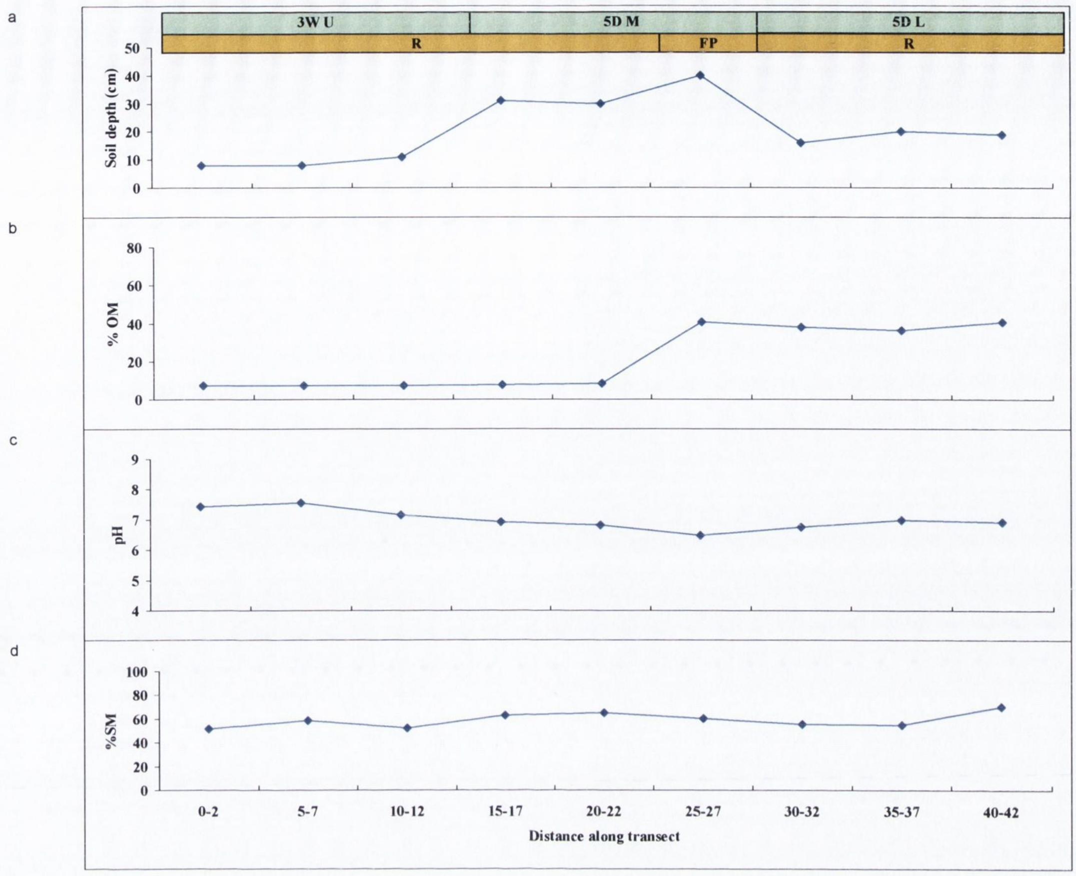

Figure 3.3: Variation in a) Soil depth; b) OM; c) pH and d) SM along the flooding gradient in Gortlecka. OM values are the mean of duplicate sub-samples. Green bars indicate vegetation; 3W U = *Rhamnus* Wood (upper); 5D M = Sedge Fen (middle) and 5D L = Sedge Fen (lower). Brown bars indicate soil type; R=Rendzina; FP = Fen Peat.

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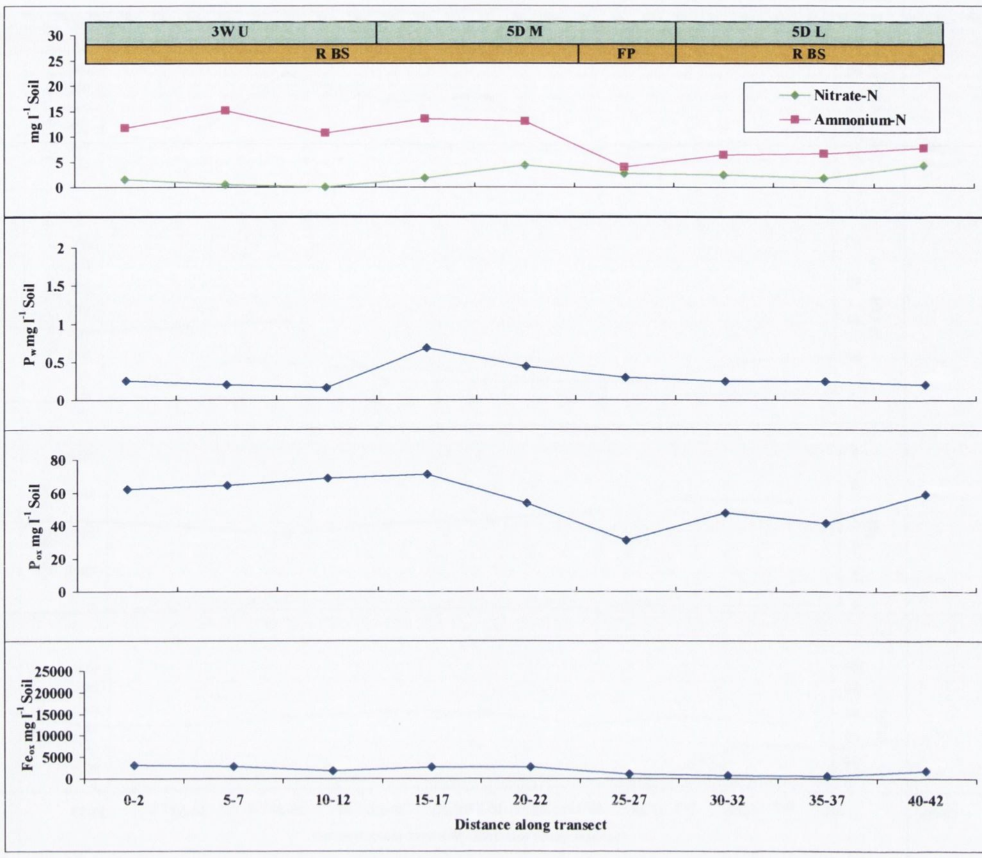

Figure 3.3: Variation in e) NO_3-N and NH_4-N; f) P_w and g) P_{ox}; h) Fe_{ox} along the flooding gradient in Gortlecka. Values are the mean of duplicate sub-samples. Green bars indicate vegetation; 3W U = *Rhamnus Wood* (upper); 5D M = Sedge Fen (middle) and 5D L = Sedge Fen (lower). Brown bars indicate soil type; R=Rendzina; FP = Fen Peat.

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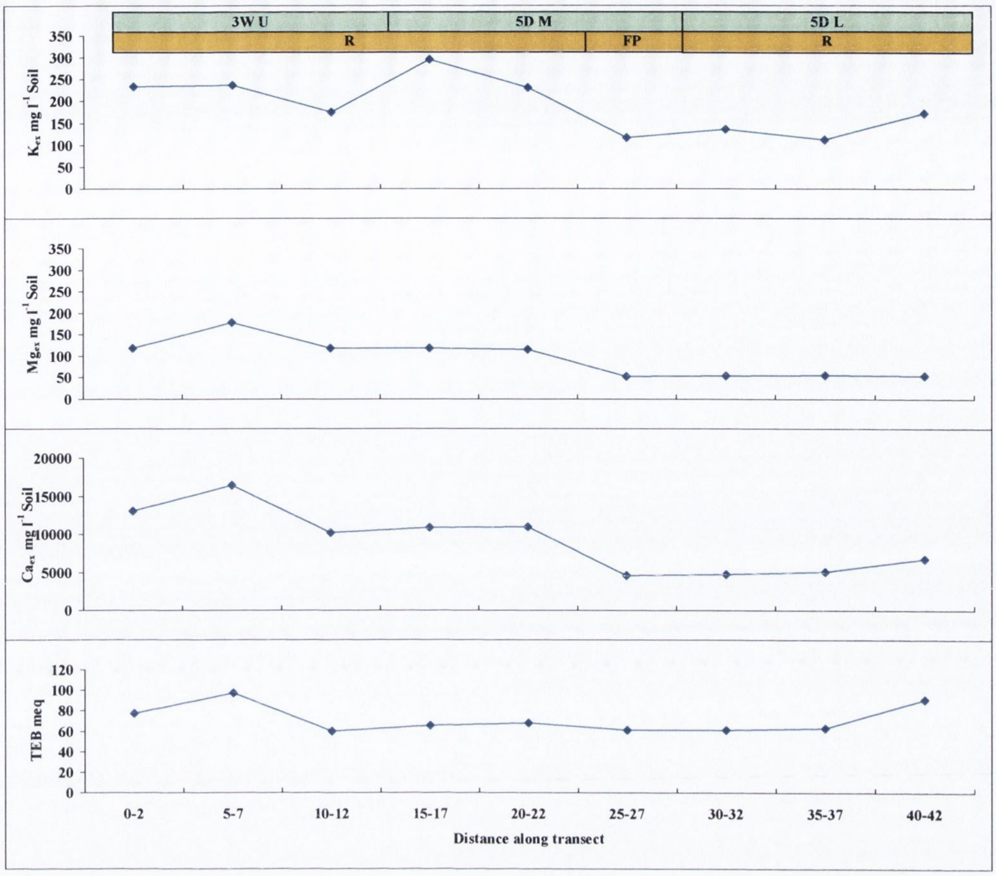

Figure 3.3: Variation in j) K_{ex}; k) Mg_{ex}; l) Ca_{ex} and m) TEB along the flooding gradient in Gortlecka. Values are the mean of duplicate sub-samples. Green bars indicate vegetation; 3W U = *Rhamnus* Wood (upper); 5D M = Sedge Fen (middle) and 5D L = Sedge Fen (lower). Brown bars indicate soil type; R=Rendzina; FP = Fen Peat.

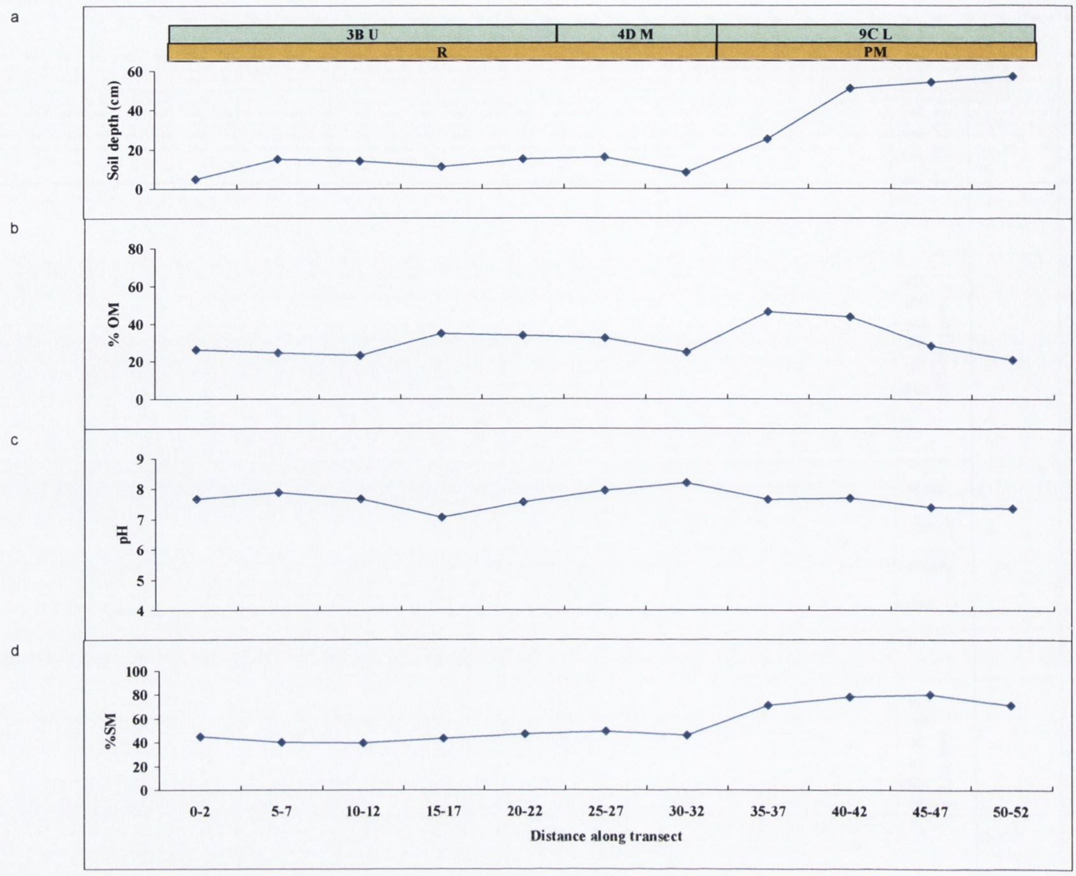

Figure 3.4: Variation in a) Soil depth; b) OM; c) pH and d) SM along the flooding gradient in Cooloorta. OM values are the mean of duplicate sub-samples. Green bars indicate vegetation type; 3B U = Sedge Heath (upper); 4D M = *Schoenus* Fen (middle) and 9C L = Marl Pond (lower). Brown bars indicate soil type; R = Rendzina; PM = Peat Marl.

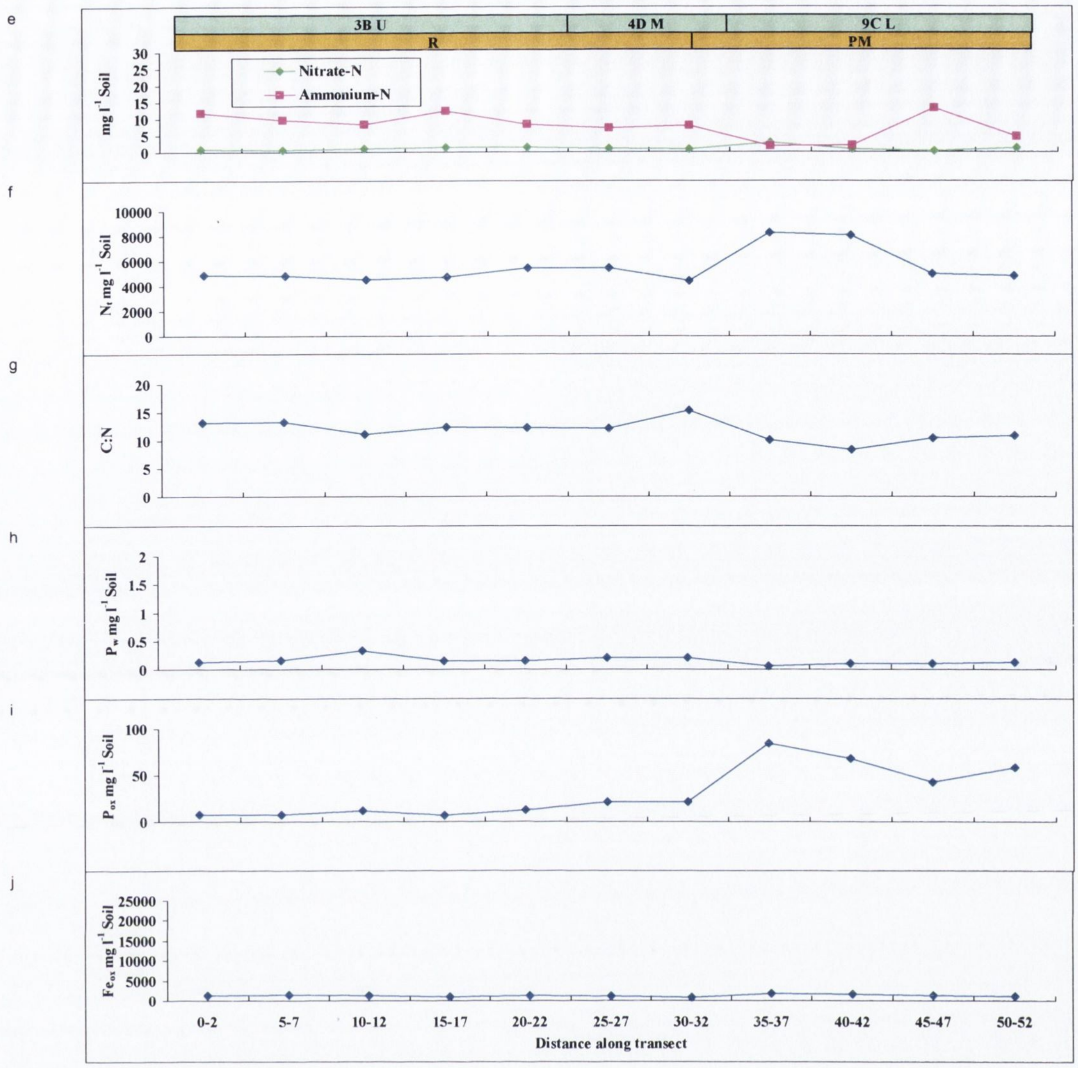

Figure 3.4: Variation in e) NO_3-N and NH_4-N; f) N_t; g) C:N; h) P_w; i) P_{ox}; j) Fe_{ox} along the flooding gradient in Cooloorta. Values are the mean of duplicate sub-samples. Green bars indicate vegetation; 3B U = Sedge Heath (upper); 4D M = *Schoenus* Fen (middle) and 9C L = Marl Pond (lower). Brown bars indicate soil type; R=Rendzina; PM = Peat marl.

3.3.3 Associations between soil properties, nutrient status and plant nutrient availability.

Results reported in this section relate to the overall relationships between soil non-nutrient physico-chemical characteristics and plant-nutrient availability, with particular emphasis on the associations with organic matter content. A correlation matrix of Spearman Rank r values is presented in Table 3.9 with highlighted values significant at the $p \leq 0.05$, 0.01 and 0.001 levels. Scatterplots of associations between plant-available forms of N and P and organic matter are presented in Figure 3.5. A correlation matrix of Spearman Rank r values is presented in Table 3.10 with highlighted bold values significant at the $p \leq 0.05$, 0.01 and 0.001 levels. Scatterplots of associations between TEB, plant-available forms of K, Mg, Ca and organic matter are presented in Figure 3.6.

A significant association (Table 3.9) was not detected between organic matter content and NO_3-N ($p > 0.05$), NH_4-N ($p > 0.05$) or Nt_{in} ($p > 0.05$). The overall pattern of the relationship between these plant-nutrient variables and OM lacked clear form and direction (Figure 3.5 a,b,c respectively). A significant negative association and significant positive association were found between soil moisture and NO_3-N ($p \leq 0.01$) and NH_4-N ($p \leq 0.05$) respectively (Table 3.9). A highly significant weakly negative association was detected between P_w and OM ($p \leq 0.001$) (Table 3.9, Figure 3.5 d). A wide range of P_w concentrations were associated with mineral and organic soils whereas generally concentrations of less than 0.5 mg l^{-1} were associated with peat soil types. (Figure 3.5 d). P_w was also highly significantly negatively correlated with SM ($p \leq 0.01$) and pH ($p \leq 0.001$) (Table 3.9). There was a weakly significant negative ($p \leq 0.05$, Table 3.9) association between P_{ox} and organic matter but the association lacks clear form and direction and the scatter plot is influenced greatly by outlying values. The majority of samples had P_{ox} concentrations below 300 mg l^{-1} and the outlying samples with greater concentrations were all from the lower area of Caherglassaun turlough, which had elevated P_{ox} concentrations.

In terms of K_{ex}, the relationship with organic matter was non-linearly weakly negative (Figure 3.6 a) and a significant association was not detected ($p > 0.05$, Table 3.10). A weakly significant positive association was detected between K_{ex} and SM ($p \leq 0.05$, Table 3.10). A weakly significant negative association was detected between Mg_{ex} ($p \leq 0.05$) and organic matter content (Figure 3.6 b). A positive, weakly significant association was detected between Mg_{ex} and pH and SM (Table 3.10). Significant associations were not detected between Ca_{ex} or TEB and OM ($p > 0.05$) and the associations lacked clear form and direction (Figure 3.6 c and d). Both Ca_{ex} and TEB had highly significant, positive associations with pH and SM.

Table 3.9: A correlation matrix of Spearman Rank r values between soil physico-chemical variables and N and P availability along flooding gradients within Caherglassaun, Garryland, Gortlecka and Cooloorta (n = 52, df = 50). Significant correlations are highlighted: $p \leq$ 0.05, $p \leq$ 0.01, $p \leq$ 0.001.

	SD (cm)	SM %	pH	OM %	P_w mg l^{-1}	P_{ox} mg l^{-1}	Fe_{ox} mg l^{-1}	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}
SD (cm)	1									
SM %	0.274	1								
pH	0.046	0.226	1							
OM %	0.253	0.457	0.186	1						
P_w mg l^{-1}	-0.102	-0.452	-0.575	-0.476	1					
P_{ox} mg l^{-1}	0.494	0.13	0.13	-0.293	0.157	1				
Fe_{ox} mg l^{-1}	0.018	-0.443	-0.523	-0.534	0.65	0.438	1			
NO_3-N mg l^{-1}	-0.058	-0.438	-0.438	-0.271	0.421	0.141	0.394	1		
NH_4-N mg l^{-1}	-0.37	0.319	0.074	-0.076	-0.217	-0.274	-0.144	-0.249	1	
N_{tin} mg l^{-1}	-0.357	0.126	-0.044	-0.265	-0.073	-0.082	0.089	0.16	0.863	1

Table 3.10: A correlation matrix of Spearman Rank r values between soil physico-chemical variables variables and K_{ex}, Mg_{ex}, Ca_{ex} and TEB along flooding gradients within Caherglassaun, Garryland and Gortlecka (n = 28, df = 26). Significant correlations are highlighted: $p < 0.05$, $p < 0.01$, $p < 0.001$.

	SD cm	%SM	pH	%OM	K_{ex} mg l^{-1}	Ca_{ex} mg l^{-1}	Mg_{ex} mg l^{-1}	TEB meq
SD	1							
%SM	0.321	1						
pH	0.132	0.151	1					
%OM	0.391	0.287	-0.289	1				
K_{ex}	-0.009	0.411	0.271	-0.162	1			
Ca_{ex}	0.195	0.629	0.778	-0.195	0.538	1		
Mg_{ex}	0.105	0.398	0.5	-0.452	0.313	0.628	1	
TEB	0.264	0.696	0.709	-0.007	0.544	0.955	0.469	1

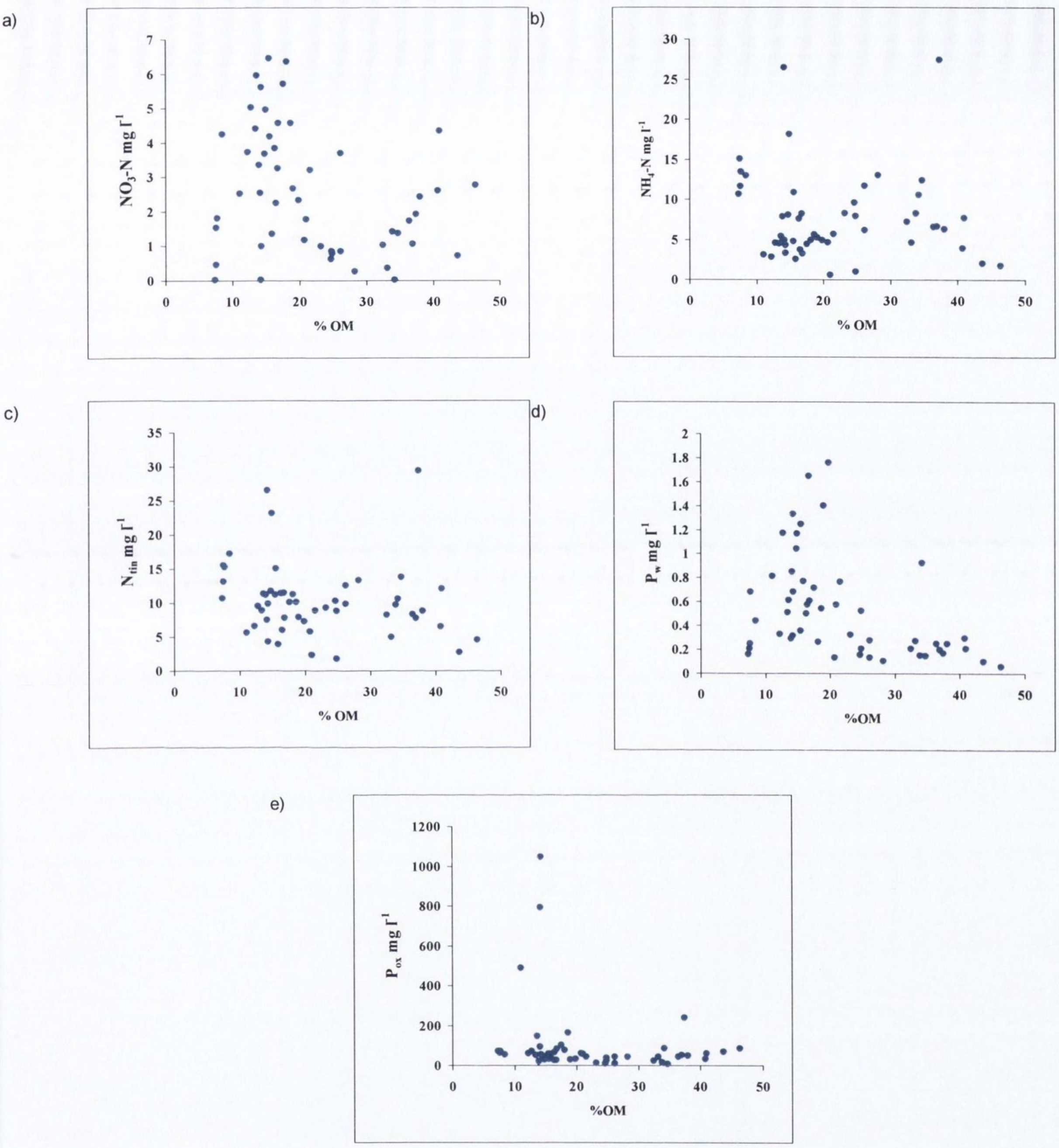

Figure 3.5: Scatterplots pf a) NO_3-N mg l^{-1}; b) NH_4-N mg l^{-1}; c) N_{tin} mg l^{-1}, d) P_w mg l^{-1} and P_{ox} mg l^{-1} against organic matter (%OM).

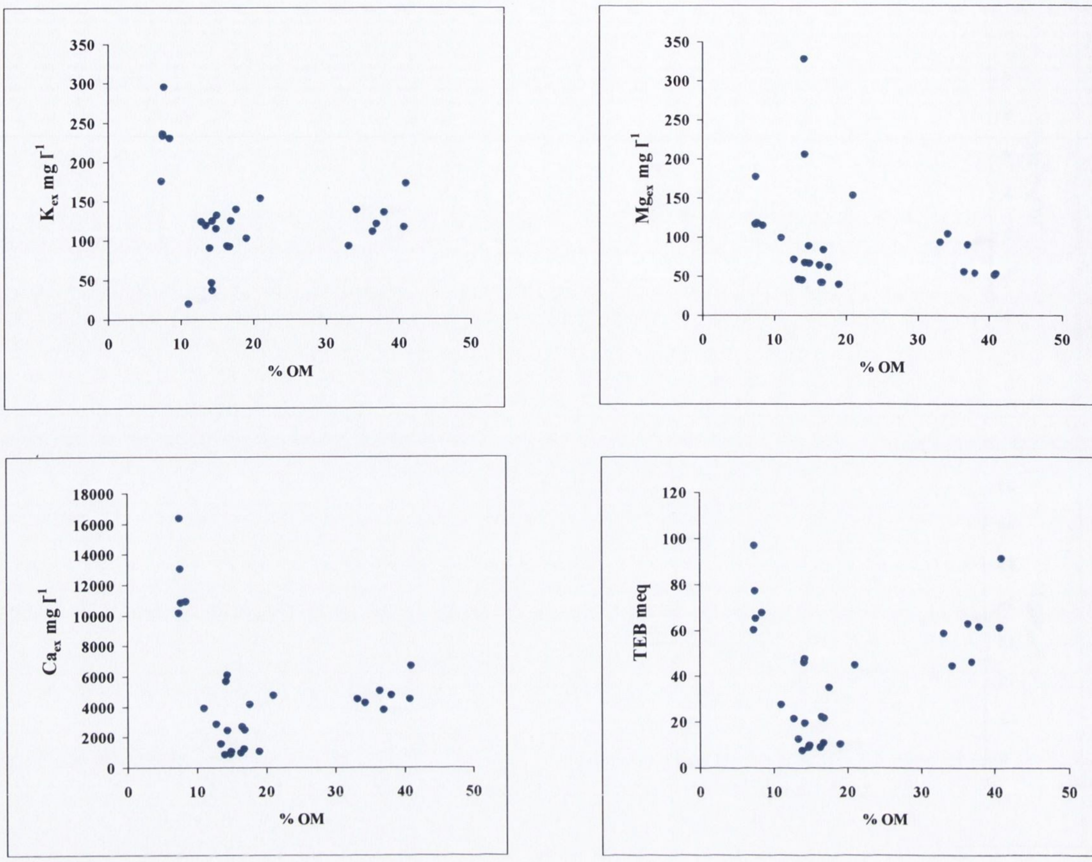

Figure 3.6. Scatterplots of a) K_{ex} mg l^{-1}; b) Mg_{ex} mg l^{-1}; c) Ca_{ex} mg l^{-1} and d) TEB meq against organic matter content.

3.4 Discussion

3.4.1 Variation in soil types and nutrient-related soil properties along turlough flooding gradients.

Soil type variations along the flooding gradients of turloughs with a similar typology had both similar and contrasting elements. Kilcolgan Series Rendzinas were the only soil type which occurred in the upper, infrequently flooded areas of Caherglassaun and Garryland in the Coole-Garryland catchment. These rendzinas all had a loamy texture and semi-fibrous organic matter, however those occurring in Garryland were of a more acidic nature and gleying was also evident. Gleys were the most common soil types associated with the middle areas of both flooding gradients. However the lower areas were distinct in that Fen Peats occurred in Garryland whereas Gleys and Alluvial soils occurred in Caherglassaun. Burren Series Rendzinas with organic textures and abundant undecomposed plant material occurred in the upper areas of both Gortlecka and Cooloorta, the only contrasting upper level soil attribute was abundant snail shell marl in some of the Cooloorta rendzinas. Ungleyed Rendzinas were the most common soil type in the middle zones of each flooding gradient. However lower levels within both turloughs were distinct in that the Peat-marls occurred in Cooloorta whereas Rendzinas occurred in Gortlecka.

The relationships between flooding susceptibility and individual non-nutrient properties were less clear than relationships with broad soil groups, and presented complex patterns. There were distinct contrasts in the variation trends of soil depth, organic matter content, pH and soil moisture among Garryland and Caherglassaun. Upper and lower areas in Garryland had contrasting non-nutrient soil properties whereas within Caherglassaun, although supporting different soils types, the upper and lower levels had similar soil depths and organic matter contents. Contrasting trends of non-nutrient soil property variation also occurred within Gortlecka and Cooloorta. In relation to soil depth, shallow soils of a similar depth occurred in the upper and lower levels of Gortlecka whereas within Cooloorta deeper soils relative to the upper and middle zones occurred in the lower zone. Relatively higher organic matter contents were associated with the lower area of Gortlecka whereas within Cooloorta upper and lower levels had similar OM contents. There was no clear relationship between pH or SM variation and flooding susceptibility within either of these East Burren catchment turloughs.

The shallow nature of soils recorded in the upper areas of the four turloughs, the majority of which are < 20 cm deep, is in keeping with previous unpublished research by MacGowran (1985) in which the author states that several variants of shallow rendzinas are associated with the highest level in turloughs on both glacial till and limestone bedrock.

MacGowran (1985) states that deep peat and marl substrates are generally associated with the basin floor areas of turloughs, however shallow substrates were often recorded in these frequently flooded lower areas of turloughs investigated in this thesis. Often shallow soils and permeable bedrock, which are commonly associated with limestone grasslands, combine to create an environment in which seasonal soil desiccation is prevalent (Moles *et al.* 2003). Rendzinas, particularly coarse textured rendzinas, present an over-drained situation (Jeffrey, 2003) and MacGowran (1985) notes that desiccation of the upper level turlough rendzinas is common during the summer season. Shallow soils (< 20 cm) in lower turlough areas may also be prone to dessication during summer months and potentially experience extremes of drying and re-wetting as lower zones are inundated with pulses of floodwater. Large flushes of mineral N and P have been reported for re-wetted soils and sediments as a consequence of drying-induced microbial cell lysis (e.g. Birch, 1960; Qiu and McComb, 1995). As mentioned in Section 3.2, measurements of soil moisture content are limited in their use as indicators of soil desiccation. Most soils along the turlough flooding gradients did not indicate a desiccated moisture status. However, four soil samples along the Caherglassaun flooding gradient had soil moisture contents < 37.9%, indicating a potentially desiccated soil condition. These soils were associated with soil depths less than 30 cm and were associated with upper, middle and lower areas along the flooding gradient. The shallow alluvial mineral soils in the lower zone of Caherglassaun, which pulses frequently with floodwater, and the shallow organic rendzinas in the infrequently flooded lower zone of Gortlecka turlough would be expected to experience varying degrees of desiccation and contrasting patterns of nutrient flushing due to differences in texture and organic matter content.

Findings reported in Chapter 2 showed that turloughs within the East Burren catchment were found to have significantly high OM contents and more peaty soil types than Coole Garryland turloughs. Accordingly, higher ranges of OM contents were recorded along the Gortlecka and Cooloorta flooding gradients in comparison to those recorded along the flooding gradients of Garryland and Caherglassaun. It would be expected that the lower zones of turloughs, which are generally under a greater annual duration of flooding and prolonged conditions of anerobiosis than the upper and middle elevations, would have elevated OM contents based on the understanding of organic matter accumulation processes in wetlands (Sahrawat, 2004). However, there was no consistent distinction between the OM content of the lower zones relative to the upper and middle zones within turloughs associated with either catchment. The lower areas of Gortlecka and Garryland had higher organic matter contents relative to the upper and middle areas of each flooding gradient. However similar distinctions in OM content between between the elevations in Caherglassaun or Cooloorta were not observed.

The processes driving and influencing organic matter decomposition are thought to be extremely complex in turloughs and the variability in organic matter accumulation patterns may be linked to the presence of permanent yet highly fluctuating pools associated with Caherglassaun and Cooloorta, which may wash-away soil organic matter contents during floodwater pulses.

A clear link between the vegetation communities, nature of OM and OM content was evident along the flooding gradients suggesting that differing turlough vegetation communities exert a major influence on turlough soil organic matter contents. These results suggest that shifts in the nature of OM from semi-fibrous to fibrous is related to changes in vegetation type from grassy communities to sedge and aquatic communities. The influence exerted by the frequency and duration of flooding on the spatial pattern in the nature of organic matter content recorded along the turlough flooding gradients is thought to be primarily via the nature of the vegetation communities it selects for and secondarily by the reduced rates of decomposition.

Within wetlands numerous factors influence soil pH and Ponamperuma (1972) states that the pH of both acidic and alkaline mineral soils approaches neutrality upon saturation. The neutral pH status in the lower zones of Caherglassaun and Garryland in contrast to the more acidic upper and middle areas may have been induced by the higher soil moisture contents. The more alkaline pH status along the Cooloorta flooding gradient in contrast to Gortlecka may be related to the presence of snail shell marl, which would be expected to increase the soil alkalinity.

3.4.2 Variations in plant-nutrient availability along turlough flooding gradients and their relation to soil type and flooding susceptibility.

3.4.2.1 Nitrogen

The N content of soils is very diverse ranging from less than 0.1% in desert soils to over 2% in highly organic soils, and 97-99% of this N in soils is present in organic forms that are not directly available to plants until after mineralization has occurred (Haynes, 1986). For the limited number of samples from Garryland and Cooloorta for which N_t and N_{tin} were both measured, organic N was found to account for 98.9-99.9% of the N_t which indicates that plant available forms of inorganic N in turlough soils are comparatively low and may be limiting plant productivity. Along both flooding gradients variations of N_t mirrored variations of OM. In a general sense, the importance of organic matter in soil cannot be over emphasised in view of its role in the maintenance of soil fertility and in particular nitrogen fertility (Sahrawat, 2004).

The major factors that influence the rate of organic matter formation also determine the mineralization/immobilisation balance of N (Swift *et al.* 1979), thus the accumulation of soil N closely follows that of soil organic matter (Rosswall, 1976).

The relationships between organic matter content in turlough soils and plant-available N observed in this thesis suggest that high organic matter contents do not reflect high concentrations of plant-available N. This highlights the importance of measuring both organic and inorganic forms of N in studies to improve understanding of turlough soil fertility. The processes, such as anaerobiosis, that facilitate the accumulation of soil organic matter in turlough soils may inhibit the mineralisation and nitrification processes that drive plant-nutrient availability. Craft and Chiang (2002) measured organic matter accumulation and the forms and amounts of soil N across transects from fresh water depressional wetlands into pine forests of southwestern Georgia and found that plant available N (NO_3-N), organic and total N increased and the C:N decreased from upland to wetland soils. The ratio of carbon to nitrogen (C/N ratio) indicates generally the degree of decomposition of organic matter; a ratio between 8 and 15 is considered satisfactory and indicates conditions favourable to microbial activity. Ratios higher than 15 are associated with a slower decomposition rate and with the accumulation of raw organic matter or, in more extreme cases, with peat development, and are indicative of unfavourable conditions for microbial activity (Finch, 1971). The ranges of C:N within Garryland are within this range whereas four samples from turloughs within Cooloorta have a C:N greater than 15, which may indicate reduced decomposition rates.

Fluxes of plant-available forms of N along the flooding gradients of Caherglassaun and Garryland had both similar and contrasting elements. Davy and Taylor (1974) report that soil N concentrations less than 15 mg l^{-1} reflect a low N fertility status and the majority of samples along both flooding gradients had N concentrations less than this threshold. This also suggests that these soils are experiencing N deficiency which may be limiting productivity within both turloughs. The similarly low concentrations of the two forms of plant-available N along the flooding gradient in Caherglassaun indicate an inhibition of NH_4-N production via mineralisation or rapid denitrification along the entire flooding gradient. The diverging and converging trend of variation in both forms of plant available N along the Garryland flooding gradient indicate that N cycling is proceeding at different rates along the flooding gradient. The extremely low concentrations of both forms of plant available N in the Gley soils may be the result of leaching and/or denitrification. The peaks in NH_4-N (>25 mg l^{-1}), both associated with extremely low concentrations of NO_3-N, in the lower zones of both turloughs are both related to soils with a high soil moisture content. High soil moisture contents are thought to inhibit nitrification and this inhibition may have resulted in these elevated concentrations.

Fluxes of plant-available forms of N along the flooding gradients of Gortlecka and Cooloorta also had both similar and contrasting elements. The majority of samples along both flooding gradients had N concentrations less than 15 mg l^{-1} which suggested that N may be limiting productivity within both of these turloughs. Trends in the relative amounts of both forms of plant-available N were similar in both turloughs. NH_4-N and NO_3-N concentrations differed by an order of magnitude in the upper level Rendzinas within both turloughs. The highest concentrations of NH_4-N and lowest concentations of NO_3-N occurred in the upper level rendzinas suggesting that nitrification processes may have been inhibited within these regions.

The lower concentrations of both forms of plant-available N in the lower areas relative to the upper areas of both turloughs suggests that N mineralisation processes may be at a reduced rate in these areas. Along both flooding gradients much greater variations were associated with NO_3-N than NH_4-N suggesting that both turloughs are characterised by high degrees of spatial variation in nitrification rates. The NH_4-N peak in the lower zone of Cooloorta was associated with the most saturated soil.

Because of the complex interactions of the many factors affecting the supply of NH_4-N and NO_3-N in soil (Haynes and Goh, 1978) only very broad generalisations on nitrogen supply in the turloughs investigated can be made. Clear relationships were not discernible between soil type and plant-available forms of N within either pair of turloughs most likely due to soil moisture influences. Strong negative and positive associations were recorded between soil moisture and NO_3-N or NH_4-N respectively. Soil moisture is likely to exert a positive influence on NH_4-N concentrations and a negative influence on NO_3-N concentrations. Aeration is essential for nitrification as oxygen is an obligate requirement for all nitrifying bacteria (Paul and Clark, 1989). Nitrification is therefore suppressed in water-logged soils by the reduced aeration (Haynes and Goh, 1978), whereas general mineralization reactions producing NH_4-N are less sensitive to water-stress resulting in NH_4-N accumulation in water-stressed soils (Paul and Clark, 1989). Zak and Grigal (1991) investigated nitrogen mineralization, nitrification and denitrification in upland and wetland ecosystems and concluded that nitrogen availability in the wetland ecosystem is probably more limited by seasonal inundation and anaerobic conditions than by organic matter content and quality. The observed relation between soil moisture content and N availability within the turloughs studied suggests that nitrogen availability is likely to be more heavily influenced by seasonal inundation than by organic matter content. Zak and Grigal (1991) note that even in east-central Minnesota where landscape changes are subtle, rates of N cycling can differ by an order of magnitude over relatively short distances. Differences in N cycling along topographic gradients can arise through the influences of temperature, moisture and substrate availability on microbial activity (Schimel, *et al.,* 1985; Davidson and Swank, 1987; Burke, 1989; Groffman and Tiedje, 1989).

Within turloughs, relatively small differences in elevation, and hence in depth to the water Table, give rise to marked changes in plant species composition and edaphic conditions; these changes often occurred across distances of only a few metres.

Lack of terminal receptors such as ferric iron and sulphate has been proposed as a factor in slowing down the destruction of organic materials in submerged soils and sediments (Lovley, 1995; Sahrawat and Narteh, 2001; Roden and Wetzel, 2002). Sahrawat and Narteh (2001) showed that N mineralization under flooded conditions was highly significantly correlated to the amount of reducible iron. From the review of recent research on the role of iron as an electron acceptor it was concluded that reducible iron influences organic matter oxidation (Lovley, 1995) and N mineralization or ammonium production (Sahrawat, 2002) in wetland soils and sediments. A lack of electron receptors might increase the accumulation of organic matter in submerged soils and sediments. It has been postulated that solubilisation of iron, manganese and aluminium and other cations in toxic concentrations in soil solution, and products of anaerobic metabolism such as ammonia under reduced conditions, might account for slowing down in organic matter decomposition in soils and sediments (Marschner and Kalbitz, 2003) due to their deleterious effects on microbial activity. Since iron oxides and hydroxides are the predominant source of electron acceptors in wetland soils and sediments they play a dominant role in organic matter oxidation and N mineralization in wetland soils and sediments (Lovley, 1995; Sahrwat, 2002). The extremely low Fe_{ox} concentrations associated with Gortlecka and Coolorta would be expected to exert a greater influence on organic matter decomposition and associated soil nitrogen dynamics within these turloughs than in Garryland and Caherglassaun.

In most of the soils sampled from each turlough NH_4-N accounted for the majority of inorganic nitrogen. As a general pattern of genotypical differences among plant species, plants adapted to low soil redox potential have a preference for ammonium (Ismunadji and Dijkshoorn, 1971) whereas plants with a preference for calcareous, high pH soils utilize nitrate preferentially (Kirkby, 1967). This highlights the potential complexity of determining the influence of differing forms of plant-available N on turlough plant species, particularly within turloughs and areas within turloughs associated with low soil redox potential and calcareous deposits.

3.4.2.2 Phosphorus

P_{ox} concentrations associated with the Rendzinas and Gleys on the upper and middle slopes of the Caherglassaun flooding gradient were below the mean concentrations (381 mg l^{-1}) reported by Daly *et al.* (2001) whereas concentrations in the lower areas were in excess of this mean and towards the high end of the range (22 – 989 mg l^{-1}) . The range of P_{ox} concentrations along the Garryland flooding gradient were at the low end of this range.

Along the Gortlecka flooding gradient P_{ox} concentrations were at the extremely low end of the range and P_{ox} concentrations associated with the upper and middle level rendzinas in Cooloorta were below the minimum. Caherglassaun, Garryland and Cooloorta tend to retain pools into the summer months and higher concentrations of P_{ox} relative to the upper and middle areas may be linked to the frequent use of cattle of these areas as drinking pools. These results indicate that spatial trends in the pools of potentially plant-available P may differ among turloughs with a similar typology.

P_w was found to range between 1.3 and 24.2 mg l^{-1} across eleven soil associations representing important Irish agricultural grassland soils (Daly *et al.*, 2001). The analyses in the study were conducted on dried soils however and numerous studies have shown that P_w analyses conducted on dried soils yield higher concentrations than analyses conducted on moist soils (e.g. Turner and Haygarth, 2001; Styles *et al.* 2004). Styles *et al.* (2004) investigated the effect of drying soil samples, and consequences for comparing P dynamics between soils and seasons, on common soil associations in the Mask catchment, and mean water-extracTable P in moist samples did not exceed 5 mg P Kg $^{-1}$ for moist soil analyses. P_w concentrations along the Caherglassaun and Garryland flooding gradients reflect an oligotrophic condition and P_w concentrations along the Gortlecka and Cooloorta flooding gradients reflect an ultra-oligotrophic condition which suggests that P may be limiting plant growth within numerous vegetation types along each flooding gradient. The higher ranges of P_w associated with Caherglassaun and Garryland in comparison to Gortlecka and Cooloorta reflect the higher P_{ox} concentrations with these Coole-Garryland turloughs.

Different factors are thought to influence P availablity along the flooding gradients of turloughs with contrasting typologies. Fe_{ox} concentrations for Irish soils have been reported to range between 4669 and 24,485 mg kg^{-1} DW, with a mean of 9179 mg kg^{-1} DW. The majority of samples along the Caherglassaun flooding gradient were at the low end of the Fe_{ox} range whereas concentrations at the high end of the range were associated with the alluvial soils at the lower area. All samples along the Garryland flooding gradient had Fe_{ox} concentrations below 9179 mg kg^{-1} DW. Extremely low Fe_{ox} concentrations were associated with the Gortlecka and Cooloorta flooding gradients.

The higher Fe_{ox} concentrations associated with the Coole Garryland turloughs reflect the high mean Fe_t concentrations associated with this catchment noted in Chapter 2. Greater concentrations of Fe_{ox} along the flooding gradients of Caherglassaun and Garryland suggest that there are greater amounts of reducible iron in Coole-Garryland, which would be expected to influence P_w concentrations. Indeed, there was a strong positive general association between P_w and Fe_{ox}. Khalid *et al.* (1977) and Willett and Higgins (1978) studied some of the factors involved in the sorption and release of phosphate in anaerobic systems.

They concluded that of all the soil properties measured, oxalate extracTable iron was the most important contributor to sorption of phosphate in anaerobic soils. Solis and Torrent (1989) found P-sorption capacity of soil to be highly correlated with Fe oxide and clay content, and that $CaCO_3$ plays a less important role in P sorption. The phosphate chemistry of soils which are seasonally waterlogged was studied by Simpson and Williams (1970) and Willett (1982). They found decreases in phosphate availability after short periods of flooding and drying, a finding with considerable significance for the residual value of fertiliser phosphate topdresses onto soils which are seasonally waterlogged. The sorption and release of native and added phosphate in aerobic soil has been shown to be affected by pH, the amount and type of clay minerals, organic matter and extracTable iron and aluminium oxides (Bradley *et al.*, 1984). Patrick and Khalid (1974) attributed increases in phosphate availability under anaerobic conditions to the change brought about in ferric compounds by soil reduction. While ferric compounds bind orthophosphate more firmly than the ferrous forms, they have less surface areas exposed. Evidence for the reduction of ferric compounds is the increase in oxalate-extracTable iron that they found. The greater Fe_{ox} concentrations associated with the Coole Garryland soils suggests that the processes outlined above would exert a greater influence on phosphate availability, and associated spatial variability, within Coole Garryland turloughs than in turloughs located in the East Burren catchment.

3.4.2.3 K_{ex}, Ca_{ex}, Mg_{ex}, TEB

K_{ex} concentrations along each of the flooding gradients were at the low end of the range reported for a range of Irish soil types reported by Styles (2004). He reported that K_{ex} ranged between 154 and 789 mg kg $^{-1}$ DW with a mean of 283 mg kg DW^{-1}. K_{ex} concentrations along the Caherglassaun and Garryland flooding gradients were below the minimum reported by Styles (2004). Along the Caherglassaun flooding gradient concentrations associated with the alluvial soils lower area were extremely low (< 50 mg l^{-1} soil). An obvious relation between soil type or elevation and K_{ex} variation was not evident along the Garryland or Gortlecka flooding gradients. The potassium status of soils depends greatly on soil parent material and its degree of weathering.

Histosols (organic soils) are generally low in K, while young soils derived from materials rich in K-bearing minerals such as alkali feldspars, Ca-Na feldspars and micas are associated with high K contents (Graham and Fox, 1971).

In soils in which weak adsorption bonds dominate, the K^+ is very mobile and can easily be replaced by other cation species such as Ca^{2+}, Mg^{2+}, and H^+ and is thus prone to leaching.. These processes may account for the low K_{ex} and high Ca_{ex} concentrations associated with the soils along each flooding gradient.

Potassium in the soil solution and on the planar surfaces can be easily absorbed by plant roots and can also be translocated vertically into the deeper soil layers. Mg_{ex} concentrations were also low along the extent of each flooding gradient. Styles (2004) reported that Ca_{ex} ranged between 784 and 11, 930 mg kg^{-1} DW, with a mean of 4226 mg kg^{-1} DW. Ca_{ex} Concentrations within the high end of this range, and often higher than the maximum, were recorded along the Gortlecka flooding gradient and highest concentrations were associated with the upper and middle elevations. Low to medium concentrations were associated with the Garryland and Caherglassaun flooding gradients and highest concentrations were associated with the lower elevations. These results reflect the contrast in hydrochemical alkalinity among the two catchment types. TEB variation closely mirrors Ca_{ex} variation along each flooding gradient, which was the dominant cation. Accumulated organic matter in wetland soils improves their general fertility status, cation exchange capacity and nutrient retention capacity (Sahrawat, 2004). There was no relationship observed between TEB and OM however. The strong relations between TEB, SM, pH and Ca_{ex} suggest that soil moisture and alkalinity potentially exert major influences, and potentially have more important roles than OM, on turlough soil nutrient availability.

Interpreting the variabilities (CVs) of soil properties observed along the flooding gradients of each turlough is hindered by a lack of readily comparable information, particularly for wetlands, in the literature. Beckett and Webster (1971) conducted a useful review of soil variability and compiled available information, from a wide range of sources, on the coefficients of variation associated with a range of soil properties. One aspect of this review compared the coefficients of variation for within-field variability and CVs of the various soil properties were compared to this information to provide a relative assessment of the degree of turlough soil property variability. One of the major conclusions of the Beckett and Webster (1971) review was that soil variability (CVs) increase with the size of area sampled and CVs above 100% are indicative of skewed distributions. The median for a range of CVs for available N (25-30%), available P (45%), available K (70%), available Mg (45%), available Ca (30%) and OM (25-30%) were reported for fields of various sizes and were compared with the CVs recorded along the turlough flooding gradients.

Beckett and Webster (1971) acknowledge that in comparable areas in the natural landscape, CVs for available N, P and K would be expected to be less by half or a quarter because of fertiliser additions and that grazing greatly influences the variability of these soil properties. The CVs for NO_3-N, NH_4-N and N_{tin} were markedly greater than 30% and were often in excess of 50% along flooding gradients of each transect.

Along the turlough flooding gradients the CVs for P_w and P_{ox} were also generally greater than 45%. K_{ex} variation along the turlough flooding gradients are distinctly below 70%, however, and are closer to the variability associated with natural landscape situations (35%). Plant-available forms of N and P therefore are highly variable in turloughs and it may require large numbers of samples to estimate mean N and P status satisfactorily, particularly within larger turloughs. Based on this information, attempts to quantify soil nitrogen and phosphorus dynamics within turloughs should take into account this variability and numerous within-turlough experimental sites would be advisable. Caherglassaun and Garryland are more heavily grazed than Gortlecka or Cooloorta however there was no clear distinction in the degrees of variation in available N or P among these turloughs. This suggests that turloughs are characterised by high degrees of variation independent of within-management conditions. The comparably low degrees of variation associated with K_{ex} within Caherglassaun, Garryland and Gortlecka may be linked to the highly mobile nature of this cation creating homogenous soil potassium conditions within turloughs, irrespective of management conditions.

Beckett and Webster (1971) acknowledge that the median CVs reported for OM, available Ca and available Mg are similar to comparable areas in the natural landscape. The variation in Mg_{ex} along the flooding gradients of Caherglassaun (39%), Garryland (45%) and Gortlecka (46%) were close to 45%. This indicates that meaningful assessments of Mg_{ex} would require a similar number of samples collected along each transect. The CVs of Ca_{ex} were markedly in excess of 30%. This high Ca_{ex} variability would be expected to be related to the patchy nature of marl deposition and shell marl accumulation within turloughs. Finally, the wide range of CVs (15-77%) associated with OM along the four turlough flooding gradients are most likely linked to varying hydrological conditions and vegetation communities associated with the different flooding gradients. Future efforts to quantify the influence of soil organic matter on nutrient dynamics should take such within-turlough OM variations into account. In summary, the soil property CVs exhibit a considerable range of values along each transect. Differences appear to exist between the natural variability of certain turlough soil properties and some will be more easily estimated than others. These results highlight the requirement for detailed preliminary site investigations prior to conducting experimental studies on soil nutrient dynamics.

3.5 Conclusions

<u>The main findings of work presented in the chapter are:</u>

- Soil type variations along the flooding gradients of turloughs with a similar typology had both similar and contrasting elements. Kilcolgan Series Rendzinas and Gleys were characteristic of the upper and middle elevations of Caherglassaun and Garryland whereas Fen Peats were associated with the lower area of Garryland and Gleys and alluvial soils occurred in the lower area of Caherglassaun. Similarly the distinction between Cooloorta and Gortlecka occurred within the lower area, where Peat-marls were associated with the former and Burren Series Rendzinas were associated with the latter. The relationships between flooding susceptibility and individual nutrient-related properties were less clear than relationships with broad soil groups, and presented complex patterns. These results highlight the requirement for soil type mapping and preliminary site assessments of individual turloughs prior to soil nutrient assessments and/or conducting soil nutrient dynamic experiments.
- The plant-available forms of N and P recorded along the flooding gradients of Caherglassaun and Garryland reflected an oligotrophic condition whereas those recorded along the Gortlecka and Cooloorta flooding gradients reflected an ultra-oligotrophic condition.
- NO_3-N varied to a greater extent than NH_4-N along the Caherglassaun flooding gradient whereas a greater degree of NH_4-N variation in comparison to NO_3-N was associated with Garryland. NO_3-N variations were greater than variations of NH_4-N within both Gortlecka and Cooloorta. Strong negative and positive associations were observed between soil moisture and NO_3-N or NH_4-N respectively. Spatial patterns of the different forms of plant-available N at any given sampling occasion are potentially driven by spatial patterns of soil desiccation and saturation rather than by variations in soil type and/or the flooding susceptibilities associated with the different elevational zones.
- Turloughs from both catchments were characterised by high degrees of variation in plant-available P and there were no obvious relationships between P_w variations and soil type/flooding susceptibility. There were strong negative associations between P_w and SM, pH and OM. P_w was strongly positively associated with Fe_{ox} which suggests that reducible iron in turlough soils may be an important factor in determining P availability in turlough soils. Fe_{ox} was markedly lower along the Gortlecka and Cooloorta flooding gradients than within Caherglassaun and Garryland, and it would therefore be expected to exert different degrees of influence on P dynamics within the different turlough types.

- Concentrations of plant-available forms of K, Mg and Ca were low along the Caherglassaun, Garryland and Gortlecka flooding gradients and there was no obvious relationship with soil type and/or flooding susceptibility along the flooding gradients. SM and pH were strongly positively associated with Ca_{ex} and TEB, highlighting the importance of the influence of soil alkalinity on turlough soil nutrient spatial patterns.
- Variations in plant-nutrient availablity along the flooding gradients suggest that nutrient cycling is proceeding at different rates throughout the turlough. Further studies are required to quantify these rates and these within-site studies should take into account spatial variations in soil types, vegetation types, organic matter contents, soil moisture conditions and soil alkalinities.
- The results presented in this chapter highlight that different soil properties vary to different extents within turloughs with the same typology. This emphasises the individual nature of turloughs and the reported within-site spatial variations present major challenges for soil nutrient assessment. Soil nutrient assessments for conservation assessment purposes should take such spatial variations into account, with particular focus on soil moisture conditions at the time of sampling.

CHAPTER 4. TEMPORAL VARIATION OF PLANT-AVAILABLE NUTRIENTS IN TURLOUGH SOILS

4.1. Introduction

Catastrophic events, such as flooding or drainage, separate periods of homogeneity within ecotones (Pinay *et al.,* 1990), a situation which is well represented by turlough systems due to the seasonal (although not strictly seasonal) nature of inundation. In an annual and general context, seasonal variation is driven by major flood events and includes two periods of relative homogeneity during both the winter months, when basins are completely inundated, and during the drained summer period. In the context of soil nutrient cycling, anaerobic processes dominate during the winter period and during the summer period soils dry out and processes generally become terrestrial. Temporal variations in available forms of plant-nutrient concentrations in turloughs during the "terrestrial" phase are thought to be driven by numerous factors including rates of nutrient cycling processes, such as mineralisation of organic matter.

Crawley (1997) states that the seasonal nature of many environments imposes a regular temporal pattern on many terrestrial soil nutrient cycling processes, such as decomposition, which are highly influenced by wetness and temperature. Temporal scales of decomposition may range from a few hours when leachates from foliage are degraded, to several decades, as the more resistant compounds are degraded (Crawley, 1997). The range of temporal scales of variation has implications for their influence on vegetation. At the level of the individual plant, temporal variations within the lifetime of the plant are most relevant whereas gross temporal patterns in availability are most relevant to investigate coarse-scale species distributions (Bazzaz and Wayne, 1994). In a seasonal context, within temperate ecosystems there is a pulse of organic matter deposition in autumn and also a peak of decomposition in spring or summer corresponding to periods of maximum microbial activity leading to a clear temporal pattern in the production of inorganic N (Howard-Williams, 1985). Bonde and Roswall (1987) reported on the seasonal variation of potentially mineralisable nitrogen in four cropping systems and they found that the amount of mineralisable N decreased during the growing season and increased in autumn as a result of organic matter input. These studies emphasise that temporal variation in soil nitrogen dynamics should be documented if we are to understand the mechanisms that determine the fate of N in a particular ecosystem.

High sample variability, and the interference of standard soil drying procedures in the detection of seasonal variation (Pote *et al.,* 1999a), have limited the number of studies published on the seasonal variation in soil P characteristics. However, there are a number of studies which indicate that soluble total phosphorus, especially Olsen P (Magid and Nielsen, 1992; Tate *et al.,* 1991a), and desorbable P (Kuo and Jellum, 1987; Pote *et al.,* 1999a; Sharpley *et al.,* 1995a) vary seasonally. Microbial populations are especially important in P cycling (Brookes *et al.,* 1984) and the same conditions of wetness and warmth that encourage microbial mineralization of organic P spur maximum plant growth and inorganic P uptake (Chaneton *et al.,* 1996; Saunders and Metson, 1971; Tate *et al.,* 1991a). Conversely, during the same cool conditions under which plant growth slows, debris may accumulate encouraging P immobilisation through microbial uptake (Perrott, *et al.,* 1990; Tate *et al.,* 1991a) and the accumulation of plant debris resulting in increases in total organic P and total P concentrations in soils (Dormaar, 1972; Daly, 1999). Seasonal variations in physicochemical processes are not as well understood as those for biological cycling of P. Chemical processes potentially contributing to seasonal variations in soil P fraction equilibria include physical and/or chemical mobilisation (desorption) of inorganic P from particulate to dissolved forms compared with physical and/or chemical immobilisation (adsorption) of solution inorganic P (Rubaek and Sibbesen, 1995). Saunders and Metson (1971) noted that soil P retention (as determined by uptake of P from solution by field moist samples) decreased as the soils dried in summer, and increased again to peak in winter.

There is plentiful evidence of seasonal variation in the availability of the major soil nutrients NPK in agricultural soils (e.g. Blackmore, 1994; Russell, 1973, Pote *et al.,* 1999a) but information on the temporal variation of plant nutrients in wetland soils is limited, and absent for turloughs. Howard-Williams (1985) reviewed the cycling and retention of nitrogen and phosphorus in wetlands and reported that both the hydrology and the uptake of nutrients by wetland vegetation can vary seasonally, particularly in temperate latitudes where growth is closely coupled with temperature and day length. For example, in temperate wetlands Harrison *et al.* (1960) and Howard-Williams *et al.* (1982) found that nitrate was removed from through-flow in summer by plant growth, but no removal occurred in winter.

Even during the terrestrial phase, turlough soils would normally be expected to undergo periodic drying and rewetting even in the absence of significant flood events, and such cycles typically induce flushes of microbial activity associated with increased rates of mineralization (Birch, 1958; Birch and Friend, 1961). Grootjans *et al.* (1986) investigated the net mineralization rates in drained and undrained fen meadows with a high percentage of total nitrogen over a three year period and found that consistent trends did not occur annually within either fen meadow, with the exception that peaks of nitrogen mineralization were associated with the mid-summer period.

The effect of temporal cycles of drying and rewetting in increasing P availability, recorded by Chepkwony *et al.* (2001), was concluded to be attribuTable to increased P mineralization.

Within turloughs, temporal variations in plant-nutrient production would be expected to vary spatially principally due to variations in soil type and associated variations in the quantity and quality of organic material as a substrate for decomposers, depth and soil moisture content. During the period from April to October the lower elevations of many turloughs remain saturated and nutrient cycling would be expected to follow that of a wetland soil that never dries out, in contrast to shallow soils on the middle and upper slopes of basins which dry out completely. Grootjans *et al.* (1986) investigated the N mineralization rates within fen peats under differing hydrological conditions and found that rates were consistently 2-3 times higher in drained fen peats than in undrained fen peats over a three year period. Sah and Mickelsen (1986) investigated the changes in sorption and bioavailability of P during the drainage period of flooded-drained soils on a daily scale and found that P sorptivity decreased as soils dried out. MacGowran (1985) noted that shallow turlough soils low in organic matter on upper levels are prone to desiccation and this may inhibit biological cycling. Grootjans *et al.* (1986) report on the decreased availability of phosphate in desiccated fen meadow soils and attributed this decrease to the fixation of phosphate by hydrous oxides of iron (Patrick and Khalid, 1974). Monitoring temporal variation in plant-nutrient availability within turloughs is challenging as summer floods after a heavy and sustained period of rainfall may result in complete inundation which would be expected to interrupt aerobic nutrient cycling processes even in upper turlough areas. An improved understanding of the degree of temporal stability associated with temporal variations in nutrient availability over the course of the drained period within turloughs is therefore necessary for formulating adequate soil nutrient monitoring programmes and for an improved understanding of turlough vegetation ecology.

The principal aims of the temporal aspect of the project were to

i) compare temporal trends in plant-nutrient availablity among common turlough soil types.

ii) assess the implications of temporal variation in nutrient concentrations for mean soil nutrient assessments of individual turloughs.

4.2. Methods

4.2.1 Site selection and experimental design for comparison of temporal variation in nutrient status among broad soil groups.

Eleven common turlough vegetation types reflecting contrasting trophic conditions were selected based on the Goodwillie (1992) classification of turlough vegetation communities (Table 1.3). The vegetation types selected for study are presented in Table 4.1 and maps showing the general location of plots in each turlough are presented in Appendix A. Goodwillie (1992) vegetation maps were used to identify and delineate areas of each selected vegetation type which were verified in the field using key indicator species, and permanent plots were located in representative areas. As turloughs are generally completely flooded from November to March, the temporal variation in plant-nutrient availability was assessed between April and October 2004. In order to separate spatial from temporal variation, two permanent 3 m^2 plots were marked out in close proximity to one another within each selected vegetation type. Plots were either marked out with orange string or tent pegs depending on the levels of grazing activity. 3 m^2 plots were used in order to provide sufficient area for repeated sampling over the growing season. Flood events dictated sampling to a great extent and sampling commenced in Mid May when floodwaters had generally receded and ended in Mid September, just prior to complete inundation. It was not possible to sample plots located at lower elevations in Mid May and Mid September due to inundation of turlough floodwaters. The sampling periods included Mid May, Mid June, Early July, Mid July, Early August, Mid August and Mid September. At each sampling period, approximately 10 cores were collected in a W pattern from each plot to a 10 cm depth using a Teagasc (Irish Agriculture and Food Development Authority) corer, and were combined to form a composite sample. Soils within each plot were described according to criteria outlined in Section 2.2.5 and pairs of replicate experimental plots within each vegetation type were grouped into broad soil types.

Table 4.1: Turloughs and plant communities selected for the location of permanent plots for monitoring temporal variation in plant nutrient availablity. See Appendix C for associated vegetation maps. A = Eutrophic; B = Mesotrophic; C = oligotrophic (calcareous); D = oligotrophic (peaty); W = oligotrophic (woodland).

Plant Community	Turlough
5B. *Potentilla. reptans* (spp. poor)	Coole
5B. *Potentilla. reptans* (spp. poor)	Garryland
6A. Dry *Carex nigra*	Garryland
9B. *Eleocharis. acicularis*	Garryland
2A. *Lolium* grassland	Caherglassaun
3C. Flooded pavement	Knockaunroe
4D. *Schoenus* fen	Knockaunroe
6B. Wet *Carex nigra*	Knockaunroe
7B. Tall sedge	Knockaunroe
4W. *Potentilla fruticosa* scrub	Knockaunroe
9C. Marl pond	Knockaunroe

4.2.2 Site selection and experimental design for comparison of temporal variation in nutrient status among sampling periods within individual turloughs.

The implications of temporal variations for soil nutrient assessment (N_{tin} and P_w) of individual turloughs representative of contrasting trophic conditions was investigated. Total inorganic N (N_{tin}) was used rather than the individual forms of plant-available N (NO_3-N and NH_4-N) as the combination of the latter forms of N would most likely be used in a general soil nutrient assessment. Temporal data for more than one soil type (and associated vegetation type) were available for Knockaunroe (RBS 3C, RBS 4D, RBS 4W, PM 7B and PM 9C) and Garryland (RKS 5B, PG 6A and G 9B) and therefore focus is placed on comparing mean nutrient status among sampling periods within both of these turloughs. Based on the nutrient sensitivity assessments conducted by the National Parks and Wildlife service (Section 2.2.1) Garryland (3 = medium sensitivity to enrichment) and Knockaunroe (extremely high sensitivity to enrichment) represent the extreme ends of the turlough trophic spectrum. Repeated measures analysis was used to compare the temporal trends among sampling periods within each turlough separately.

4.2.3 Soil nutrient analyses

4.2.3.1 Soil preparation

Standard soil analytical procedures involving drying soil samples prior to analysis are generally used to assess soil nutrient status although this has been found to increase soil P desorption and solubilisation (e.g. Turner and Haygarth, 2001) and obscure seasonal variation in P desorption (e.g. Pote *et al.,* 199a). An analysis of the effect air-drying soil samples has on soil P extraction conducted by Styles *et al.* (2004) concluded that air-drying soils significantly increases laboratory P_w values and appears to reduce sample representativeness of variation in P_w between seasons. Analyses of plant available nutrients were therefore conducted on moist samples. Soils were stored for two days in polythene bags placed in cool boxes prior to preparation and analysis, and subsequently sieved through a 4mm sieve and thoroughly homogenised. For background nutrient assessments of each plot samples were oven dried for 48 hrs at 35°C and passed through a 2 mm sieve.

4.2.3.2 Laboratory analyses

In the majority of cases nutrient analyses were conducted in duplicate but in some cases, insufficient soil was collected to allow for duplicate analyses. pH and soil moisture were determined on a single representative sub-sample collected from each plot on each sampling occasion. Soils collected from each plot were analysed for pH, SM, OM, plant available forms of nitrogen (NO_3-N and NH_4-N) and P_w according to protocols outlined in Chapter 2. Section 2.2.5. One sample from each plot was analysed for P_t and N_t to determine background nutrient status.

4.2.4 Data analysis

Summary statistics were generated in Datadesk 6.0. Comparisons of temporal changes in nutrient availability (N_{tin}, NO_3-N, NH_4-N and P_w) among broad soil groups were conducted using repeated measures ANOVA as a nested model. The nested model was employed rather than multivariate ANOVA as flood events prevented sampling of some experimental plots at the beginning and end of the growing season and this model allowed for the inclusion of plots with missing data in the analysis. Missing observations are omitted only for the repeat on which they are missing; the subject can be kept in the analysis (Velleman, 1995). Factors in the nested form of a repeated measures design included Soil Type, Replicate Plot and Sampling Period.

The nested form of a repeated measures design nests the random subjects term in one of the factors, in this case replicate plot was nested in soil type. A Soil Type*Sampling Period interaction was added as we wanted to know if the different soil types were associated with contrasting temporal trends in plant-nutrient availablity over the turlough growing season/drained period. Repeated measures ANOVA as a nested model was also used to compare mean nutrient status among sampling periods within both Garryland and Knockaunroe. Where necessary, data were log transformed to achieve normality prior to repeated measures analysis. Scales were standardised among graphs to allow for visual comparison of temporal trends among soil types and among soil/vegetation types within turloughs.

4.2.5. Site descriptions

Vegetation type: 5B *Potentilla reptans* (spp. poor) (mesotrophic)

Soil type: Peaty Gley

Turlough: Inse Woods, Coole

Code: PG 5B

This is a distinctive community covering large areas of drift-filled turloughs where superficial drainage is good (Goodwillie, 1992). It consists of *Carex nigra*, *Potentilla anserina*, *Agrostis stolonifera* with a constant presence of *Potentilla reptans*, *Mentha aquatica* and *Ranunculus repens*. It is the main location for *Viola persicifolia*, with some *Viola canina,* while in certain turloughs it includes *Teucrium scordium* and *Taraxacum sect. palustris*. Inse Woods, Coole is dominated by this vegetation type and the two plots were located within the central area of the turlough (Plates 4.3 and 4.4). .

Table 4.2: Soil descriptions for Plot A and B within 5B ***P. reptans*** *(spp. poor).*

Plot	Colour	OM	Texture	Depth cm	pH	%OM	%$CaCO_3$	%Inorg	Broad soil group
A	Dark greyish brown (10 YR 4/2) with yellowish brown mottles (10 YR 5/6). Few, fine, feint, diffuse.	Semi-fibrous	Sandy clay loam	19	6.3	24.5	6.4	69.1	Gley
B	Brown (10 YR 5/3) with yellowish brown mottles (10 YR 5/6). Abundant, fine, distinct, sharp.	Semi-fibrous	Sandy clay loam	17	6.1	22.1	6.0	72.0	Gley

Plate 4.1: Coole Turlough, Co. Galway Plot A ***Lotus corniculatus, Potentilla reptans, Mentha arvensis, Viola canina, Ceratsium fontanum, Stellaria media, Agrostis stolonifera, Filipendula ulmaria, Phalaris arundinacea, Rumex crispus, Leontodon autumnale, Ranunculus repens, Carex nigra, Potentilla anserina, Rumex acetosa, Trifolium repens and Galium palustre****.*

Plate 4.2: Coole Turlough, Co. Galway PlotB ***Lotus corniculatus, Potentilla reptans, Ceratsium fontanum, Stellaria media, Agrostis stolonifera, Filipendula ulmaria, Phalaris arundinacea, Rumex crispus, Leontodon autumnale, Ranunculus repens, Carex nigra, Potentilla anserina, Rumex acetosa, Trifolium repens and Galium palustre.***

Vegetation type: 5B *Potentilla reptans* (spp. poor) (over-grazed) (mesotrophic)

Soil type: Rendzinas (Kilcolgan Series)

Turlough: Garryland

Code: RKS 5B

This is the second most dominant vegetation type in Garryland turlough and occupies 6.0 ha of this 20.4 ha site, generally occurring on the turlough margins and spurs of higher ground. Goodwillie (1992) notes that this vegetation type is usually closely grazed with species such as *Phalaris arundinacea* much reduced in height. Within this turlough over-grazing is currently a conservation issue and this vegetation type occurs in its closely grazed form. The two permanent plots were located on the northern end of the main spur of higher ground from the southern shore (Plates 4.5 and 4.6).

Table 4.3: Soil Descriptions for Plot A and B in 5B. *Potentilla reptans* (spp. poor) (grazed).

Plot	Colour	OM	Texture	Depth cm	pH	%OM	%$CaCO_3$	%Inorg	Broad soil group
A	Brown (10 YR 4/3)	Semi-fibrous	Sandy clay loam	10	6.01	21.8	6.2	71.9	Rendzina, Kilcolgan Series
B	Brown (10 YR 4/3)	Semi-fibrous	Sandy clay loam	12	6.15	22.5	6.7	70.8	Rendzina, Kilcolgan Series

Plate 4.3: Garryland Turlough, Co. Galway Plot A ***Agrostis stolonifera, Carex nigra, Galium palustre, Leontodon autumnale, Lotus corniculatus, Mentha arvensis, Plantago major, Potentilla anserine, Potentilla reptans, Ranaunculus repens, Rumex crispus, Stellaria media, Viola canina.***

Plate 4.4: Garryland Turlough, Co. Galway Plot B ***Agrostis stolonifera, Carex nigra, Galium palustre, Leontodon autumnale, Lotus corniculatus, Mentha arvensis, Potentilla anserina, Potentilla reptans, Ranaunculus repens, Stellaria media, Viola canina.***

Vegetation type: 6A Dry *Carex nigra* (eutrophic)

Soil type: Peaty Gley

Turlough: Garryland

Code: PG 6A

Dry *Carex nigra* dominates the turlough floor occupying 6.6 ha of this site. The indicator species include *Carex nigra, Agrostis stolonifera, Potentilla anserina, Plantago lanceolata, Rumex crispus, Phalaris arundinacea.* There are extensive stands of this vegetation type towards the base of many turloughs where they approach the long-lasting pools or permanent ponds. Within Garryland, this vegetation type occupies the zone between the upper areas of *P. reptans* (spp. poor) and the lower wetter ground dominated by 9B. *Eleocharis acicularis*. Despite its name there are places in which *C. nigra* is rare or absent, perhaps in response to nutrient enrichment or trampling by cattle where *P. anserina* and *A. stolonifera* may cover almost all of the ground (Goodwillie, 1992). The substrate for this community seems generally to be mineral rather than peaty and is relatively firm in summer however some of the purest stands grow on marl. The plots within this vegetation type were located on the western side of the main central spur of higher ground grading from 5B. *P. reptans* (spp. poor) to 9B. *Eleocharis acicularis (*Plates 4.7 and 4.8*)*.

Table 4.4: Soil Descriptions for Plot A and B in 6A. Dry ***Carex nigra***

Plot	Colour	OM	Texture	Depth cm	pH	%OM	$\%CaCO_3$	% Inorg	Broad soil group
A	Greenish grey (Gley 1 5/1) with brownish yellow mottles (10 YR 6/8). Many, fine, prominent, diffuse.	Semi-fibrous	Clay loam	22	6.7	28.2	6.2	65.6	Gley
B	Greenish grey (Gley 1 5/1) with brownish yellow mottles (10 YR 6/8). Many, fine, prominent, diffuse.	Semi-fibrous	Clay loam	25	6.6	29.1	6.3	64.6	Gley

Plate 4.5: Garryland Turlough, Co. Galway Plot A ***Potentilla anserina, Carex nigra, Galium palustre, Mentha arvensis, Potentilla anserina, Ranunculus repens, Galium verum, Carex panicea, Festuca ovina***

Plate 4.6: Garryland Turlough, Co. Galway Plot B ***Potentilla anserina, Carex nigra, Potentilla anserina, Ranunculus repens, Galium verum, Carex panicea, Festuca ovina***

Vegetation type: 9B *Eleocharis acicularis* (mesotrophic)

Soil type: Gley

Turlough: Garryland

Code: G 9B

Goodwillie (1992) notes that *Eleocharis acicularis* is a restricted species in turloughs but where it does occur it forms closed patches by means of its many rhizomes and these create a distinct community. The associated substrate is generally a fine peaty mud subject to frequent but intermittent flooding. 1.9 ha of this turlough is occupied by this vegetation type but in a general turlough context accounts for only 0.2% of vegetation coverage. It is extensive in the parts of Garryland that remain wet during the summer months and associated species include *Eleocharis palustris*, *Limosella aquatica*, *Litorella uniflora*, *Callitriche stagnalis* and *Polygonum* spp. The plots were located in the south-eastern turlough floor area and were dominated by the presence of *E. acicularis* and annual species on mud (Plates 4.9 and 4.10).

Table 4.5: Soil Descriptions for Plot A and B within in 9B ***Eleocharis acicularis.***

Plot	Colour	OM	Texture	Depth cm	pH	%OM	%$CaCO_3$	% Inorg	Broad soil group
A	Pinkish grey (7.5 YR 6/2) with yellowish red mottle (7.5 YR 4/6). Few, fine, distinct, sharp.	Semi-fibrous	Silty clay	45	6.5	18.2	N/A	N/A	Gley
B	Pinkish grey (7.5 YR 6/2) with yellowish red mottle (7.5 YR 4/6). Few, fine, distinct, sharp.	Semi-fibrous	Silty clay	47	6.5	16.0	N/A	N/A	Gley

Plate 4.7: Garryland Turlough, Co. Galway Plot A ***Eleocharis acicularis, Eleocharis palustris, Agrostis stolonifera, Potentilla anserina, Polygonum amphibium, Galium palustre, Juncus articulatus, Leontodon autumnale, Limosella aquatica, Polygonum hydropiper, Rorippa sylvestris***

Plate 4.8: Garryland Turlough, Co. Galway Plot B ***Eleocharis acicularis, Eleocharis palustris, Agrostis stolonifera, Potentilla anserina, Polygonum amphibium, Galium palustre, Juncus articulatus, Leontodon autumnale, Limosella aquatica, Polygonum hydropiper, Rorippa sylvestris***

Vegetation type: 2A *Lolium* grassland (eutrophic)

Soil type: Rendzina (Kilcolgan Series)

Turlough: Caherglassaun

Code: RKS 2A

This vegetation community is found on the more eutrophic fields around turlough margins and may be naturally rich, especially if there is limestone near the surface, or may be fertilised and grazed (Goodwillie, 1992). The community was usually recognised by the presence of *Lolium perenne*, *Festuca rubra*, *Trifolium repens*, *Bellis perennis*, *Cirsium arvense* and *Poa* spp. *Cerastium fontanum* and *Odontites verna* are practically restricted to this turlough community. 2A *Lolium* grassland community occupies 3.1 ha of the total turlough area of Caherglassaun (41.8 ha) and plots were located in the most extensive area of this vegetation type on the southern shore, within an area of intensive pasture with locally abundant *Rumex* spp (Plates 4.1 and 4.2). The Ellenberg Scores suggest that both plots have an intermediate fertility status.

*Table 4.6: Soil Descriptions for Plot A and B within 2A (**Lolium** grassland).*

Plot	Colour	OM	Texture	Depth cm	pH	%OM	$\%CaCO_3$	%Inorg	Broad soil group
A	Brown (10 YR 4/3)	Semi-fibrous	Sandy loam	18	5.7	12.9	4.7	82.5	Rendzina, Kilcolgan Series
B	Brown (10 YR 4/3)	Semi-fibrous	Sandy loam	22	5.9	14.7	4.5	80.9	Rendzina, Kilcolgan Series

Plate 4.9: Caherglassaun Turlough, Co. Galway Plot A ***Lolium perenne, Bellis perennis, Cardamine pratensis, Filipendula ulmaria, Galium palustre, Leontodon autumnale, Lotus corniculatus, Potentilla anserina, Ranunculus repens, Rumex acetosa, Rumex crispus, Stellaria media, Trifolium repens.*** **Average Ellenberg Score: 5. RKS 2A Plot B (Photograph N/A).**

Vegetation type: 3C Flooded pavement (oligotrophic)

Soil type: Rendzina (Burren Series)

Turlough: Knockaunroe

Code: RBS 3C

This is a distinctive habitat rather than a plant community and contains widely different vegetation depending on variations in elevation. At higher levels *Sedum acre*, *Lotus corniculatus*, and *Plantago* spp. are characteristic with *Calluna vulgaris*, *Vicia cracca* and *Antennaria dioica*. This habitat type accounts for 0.2% of turlough vegetation and occupes 0.6 ha of this 42.5 ha site. The plots were located in the upper limestone pavement of the northern shore of Knockaunroe which consists of bare limestone rock and hollows dominated by *Pteridium aquilinum*, *Calluna vulgaris* and *Rubus fruticosus* on shallow soils (Plates 4.11 and 4.12).

Table 4.7: Soil Descriptions for Plot A and B within 3C Flooded pavement

Plot	Colour	OM	Texture	Depth cm	pH	%OM	%$CaCO_3$	%Inorg	Broad soil group
A	Very dark brown (10 YR 2/2)	Semi-fibrous	Organic	8	7.4	49.4	4.3	46.3	Rendzina, Burren Series
B	Very dark brown (10 YR 2/2)	Semi-fibrous	Organic	10	7.4	39.9	4.6	40.1	Rendzina, Burren Series

Plate 4.10: Knockaunroe Turlough, Co. Clare Plot A ***Pteridium aquilinum, Calluna vulgaris, Crataegus monogyna, Rosa pimpinellifolia, Geranium sanguineum, Lotus corniculatus, Succisa pratensis, Potentilla erecta, Cirsium dissectum, Molinia caerulea***

Plate 4.11: Knockaunroe Turlough, Co. Clare Plot B ***Pteridium aquilinum, Calluna vulgaris, Crataegus monogyna, Rosa pimpinellifolia, Geranium sanguineum, Lotus corniculatus, Potentilla erecta, Cirsium dissectum, Molinia caerulea***

Vegetation type: 4W *Potentilla fruticosa* scrub (oligotrophic)

Soil type: Rendzina (Burren Series)

Turlough: Knockaunroe

Code: RBS 4W

Potentilla fruticosa scrub is characteristic of the Burren turloughs surrounded by limestone pavement. MacGowran (1985) identified a *Potentilla fruticosa* community in turloughs within the East Burren Complex, where it grows with *Rosa pimpinellifolia* and *Fissidens adianthoides*, but rarely occurs with *Frangula alnus*. This community is a variant of the Frangula wood community identified by Goodwilie (1992) where *Frangula alnus*, *P. fruticosa*, *Rhamnus* and *Rubus caesius* dominate. *Molinia caerulea, Deschampsia flexuosa and Festuca arundinacea* grow in between the shrubs. The plots were located in the upper limestone pavement of the northern shore which consists of bare limestone rock and extensive stands of *P. fruticosa* on shallow soils (Plates 4.13 and 4.14).

Table 4.8: Soil Descriptions for Plot A and B within 4W ***Potentilla fruticosa*** *scrub*

Plot	Colour	OM	Texture	Depth cm	pH	%OM	$\%CaCO_3$	%Inorg	Broad soil group
A	Very dark brown (10 YR 2/2)	Fibrous	Organic	8	7.5	35.2	4.4	60.4	Rendzina, Burren Series
B	Very dark brown (10 YR 2/2)	Fibrous	Organic	9	7.5	35.4	4.3	60.3	Rendzina, Burren Series

Plate 4.12: Knockaunroe Turlough, Co. Clare Plot A ***Potentilla fruticosa, Lotus corniculatus, Potentilla erecta, Hydrocotyle vulgaris, Cirsium dissectum, Schoenus nigricans, Potentilla anserina, Crataegus monogyna, Mentha arvensis, Filipendula ulmaria, Carex flacca, Carex nigra, Rhamnus catharticus, Molinia caerulea, Rubus caesius***

Plate 4.13: Knockaunroe Turlough, Co. Clare Plot B ***Potentilla fruticosa, Lotus corniculatus, Potentilla erecta, Hydrocotyle vulgaris, Cirsium dissectum, Schoenus nigricans, Potentilla anserina, Crataegus monogyna, Mentha arvensis, Filipendula ulmaria, Carex flacca, Carex nigra, Rhamnus catharticus, Molinia caerulea, Rubus caesius, Geranium sanguineum, Plantago lanceolata, Plantago major, Viola canina, Leontodon autumnale***

Vegetation type: 4D *Schoenus* fen (oligotrophic)

Soil type: Rendzina (Burren Series)

Turlough: Knockaunroe

Code: RBS 4D

This is an easily distinguished vegetation type in which *Schoenus nigricans* forms a regular cover of tussocks with *Molinia Caerulea*, *Carex panicea*, *Carex hostiana* and *Achillea ptarmica, Cirsium dissectum, Parnassia palustris.* It is almost never grazed due to unpalatability so it reaches a height of 40 cm or more. It grows on alkaline peat that seems to be flooded annually and retains a high water Table for most of the year. 2.9 ha of Knockaunroe is *Schoenus* fen which occupies the area between the limestone pavement and Wet *Carex nigra.* A layer of fen peat is usually associated with this vegetation type although soils are often very shallow. The plots were located in the upper limestone pavement of the Northern shore which consists of bare limestone rock and extensive stands of *S. nigricans* on shallow soils (Plates 4.15 and 4.16).

Table 4.9: Soil Descriptions for Plot A and B within 4D Schoenus *fen.*

Plot	Colour	OM	Texture	Depth cm	pH	%OM	%$CaCO_3$	%Inorg	Broad soil group
A	Very dark brown (10 YR 2/2)	Fibrous	Organic	8	7.9	41.8	17.9	40.3	Rendzina, Burren Series
B	Very dark brown (10 YR 2/2)	Fibrous	Organic	12	7.8	40.6	5.7	53.7	Rendzina, Burren Series

Plate 4.14: Knockaunroe Turlough, Co. Clare Plot A ***Schoenus nigricans, Molinia caerulea, Cirsium dissectum, Potentilla erecta, Lotus corniculatus, Rubus caesius, Achillea ptarmica, Agrostis stolonifera, Parnassia palustris.***

Plate 4.15: Knockaunroe Turlough, Co. Clare Plot B ***Schoenus nigricans, Molina caerulea, Cirsium dissectum, Potentilla erecta, Mentha aquatica, Teucrium scordium, Potentilla anserina, Lotus corniculatus, Achillea ptarmica, Galium boreale, Agrostis stolonifera, Rubus saxatilis, Carex nigra, Carex panicea.***

Vegetation type: 6B Wet *Carex nigra* (mesotrophic)

Soil type: Fen Peat

Turlough: Knockaunroe

Code: FP 6B

This vegetation type is one of the most common turlough plant communities and is characteristic of a turlough that retains some dampness into the summer with the water Table just below the surface (Goodwillie, 1992). Within Knockaunroe however 6B Wet *Carex nigra* only accounts for 0.9 ha of the total vegetation cover. The indicator species include *Carex nigra, Senecio aquaticus, Caltha palustris, Eleocharis palustris, Hydrocotyle vulgaris, Myosotis scorpioides, Juncus articulatus, Phalaris arundinacea*. The substrate is a peaty silt or even well humified peat which is slow to dry out. *Potentilla anserina, Ranunculus repens and Agrostis stolonifera* are also common throughout this vegetation type. The community grows on a broad range of habitats associated with seepage water on the sides of turloughs and static water at the base. The plots were located in the turlough floor area of the northern basin (Plates 4.17 and 4.18).

Table 4.10: Soil Descriptions for Plot A and B within 6B Wet ***Carex nigra****.*

Plot	Colour	OM	Texture	Depth cm	pH	%OM	%$CaCO_3$	% Inorg	Broad soil group
A	Dark brown (10 YR 3/3)	Fibrous	Organic	37	7.7	61.5	24.1	14.4	Fen Peat
B	Dark brown (10 YR 3/3)	Fibrous	Organic	35	8.0	54.8	13.9	31.3	Fen Peat

Plate 4.16: Knockaunroe Turlough, Co. Clare Plot A ***Carex nigra, Mentha aquatica, Ranunculus repens, Galium palustre, Ranunculus flamula, Juncus articulatus, Potentilla anserina, Agrostis stolonifera, Teucrium scordium, Carex aquatilis, Eleocharis palustris***

Plate 4.17: Knockaunroe Turlough, Co. Clare Plot B ***Carex nigra, Mentha aquatica, Ranunculus repens, Galium palustre, Ranunculus flamula, Juncus articulatus, Potentilla anserina, Agrostis stolonifera, Teucrium scordium, Carex aquatilis, Eleocharis palustris***

Vegetation type: 7B Tall sedge (mesotrophic)

Soil type: Peat-marl

Turlough: Knockaunroe

Code: PM 7B

This vegetation is recognised by the dominance of large sedges and within Knockaunroe is recognised by conspicuous tufts of *Carex elata* in the lowest basin areas (1.7 ha) that dry out for only short periods during the growing season. Variations of this plant community are found on drift or shallow peat with *Carex vesicaria* associated with the former and *Carex aquatilis* with the latter. *Carex rostrata* forms the majority of stands which may be mixed with *Carex nigra*, *Eleocharis palustris* and *Menyanthes trifoliata*. In more eutrophic turloughs *Carex acuta* is present occasionally but *Carex elata* occurs in mixture with *Phragmites australis* and *Schoenoplectus lacustris*. The plots were located in the turlough floor area of the northern basin on peat-marl soils (Plates 4.19 and 4.20).

Table 4.11: Soil Descriptions for Plot A and B in 7B Tall Sedge.

Plot	Colour	OM	Texture	Depth cm	pH	%OM	%$CaCO_3$	%Inorg	Broad soil group
A	Dark brown (10 YR 3/3). Many, fine flecks of snail shell marl (10 YR 7/1).	Semi-fibrous	Silty clay	22	8.0	29.6	52.9	17.5	Peat-marl
B	Dark brown (10 YR 3/3). Many, fine flecks of snail shell marl (10 YR 7/1).	Semi-fibrous	Silty clay	15	8.1	22.5	67.2	10.3	Peat-marl

Plate 4.18: Knockaunroe Turlough, Co. Clare Plot A ***Carex elata, Samolus valerandi, Eleocharis palustris, Phalaris arundinacea, Galium boreale, Galium palustre, Potentilla anserina, Carex aquatilis, Mentha aquatica, Ranunculus flammula, Teucrium scordium, Agrostis stolonifera, Ranunculus repens, Juncus articulatus, Agrostis stolonifera***

Plate 4.19: Knockaunroe Turlough, Co. Clare Plot B ***Carex elata, Samolus valerandi, Eleocharis palustris, Phalaris arundinacea, Galium boreale, Galium palustre, Potentilla anserina, Carex aquatilis, Mentha aquatica, Ranunculus flammula, Teucrium scordium, Agrostis stolonifera, Ranunculus repens, Juncus articulatus, Agrostis stolonifera***

Vegetation type: 9C Marl pond (oligotrophic)

Soil type: Peat-marl

Turlough: Knockaunroe

Code: PM 9C

This community is characteristic of the pool areas in highly calcareous turloughs (Goodwillie, 1992). Such turloughs are often extremely oligotrophic and the flora includes species normally associated with acidic habitats as well as those found on limestone. They are thus of peculiar ecological interest. The most distinctive species for this community are *Juncus bulbosus*, *Baldellia ranunculoides*, *Litorella uniflora*, *Potamogeton gramineus* and *Scorpidium scorpioides*. Less frequent but no less characteristic are *Samlous valerandi*, *Eleocharis multicaulis*, *Scirpus fluitans*, *Potamogeton polygonifolius* and *P. coloratus*. The community grows in shallow semi-permanent water with marl usually deposited on peat. *Scirpus fluitans* and *Carex lepidocarpa* are especially associated with peat. The predominant community at Knockaunroe is Marl Pond (20 ha), which is also common in the context of general turlough vegetation (4.8%). The associated substrate includes marl and peat-marl. The plots were located in the turlough floor area of the northern basin on marl substrates (Plates 4.21 and 4.22

Table 4.12: Soil Descriptions for Plot A and B within 9C Marl pond.

Plot	Colour	OM	Texture	Depth cm	pH	%OM	%$CaCO_3$	% Inorg	Broad soil group
A	Grey (10 YR 5/1)	Semi-fibrous	Silty clay	13	8.2	21.7	64.6	13.7	Peat-marl
B	Grey (10 YR 5/1)	Semi-fibrous	Silty clay	15	8.3	19.8	71.9	8.2	Peat-marl

Plate 4.20: Knockaunroe Turlough, Co. Clare Plot A ***Carex nigra, Agrostis stolonifera, Ranunculus repens, Carex aquatilis, Mentha aquatica, Teucrium scordium, Galium palustre, Eleocharis palustris, Ranunculus flammula***

Plate 4.21: Knockaunroe Turlough, Co. Clare Plot B ***Carex nigra, Agrostis stolonifera, Ranunculus repens, Carex aquatilis, Mentha aquatica, Teucrium scordium, Galium palustre, Eleocharis palustris, Ranunculus flammula***

4.3 Results

4.3.1 Comparison of temporal trends of plant-available N and P among broad soil groups.

P_t and N_t concentrations for each pair of experimental plots are presented in Table 4.14. Summary statistics of temporal variation in plant-nutrient availablity associated with each pair of experimental plots located within each soil type/vegetation type are presented in Tables 4.18 to 4.28. Temporal variation patterns in plant-nutrient availability associated with each soil group are presented in Figures 4.1 - 4.4.

4.3.1.1 Nitrogen

Variation in N_{tin} (total inorganic nitrogen) availability over the growing season did not differ significantly among the three broad soil groups ($p > 0.05$, log transformed data, Table 4.15) however temporal trends in NH_4-N ($p \leq 0.001$, log transformed data, Table 4.15) and NO_3-N ($p \leq 0.0001$, log transformed data, Table 4.15) did vary significantly among the three broad soil groups. It is clear that temporal trends in Ntin associated with the Rendzinas (Figure 4.1a) and Peats (Figure 4.1c) were closely similar to trends in NH_4-N (Figure 4.2 a and c) whereas trends in N_{tin} associated with the Gleys (Figure 4.1b) were more similar to temporal variations in NO_3-N (Figure 4.3b). During the growing season the dominant form of plant-available N within the Gleys is NO_3-N whereas NH_4-N is the dominant form of plant-available N in the Rendzinas and Peats. This suggests that the combination of the two forms of plant-available N (NO_3-N and NH_4-N) obscures an interesting distinction between the broad soil groups in terms of temporal variation in the dominant forms of plant-available N.

Erratic temporal trends in NH_4-N and high degrees of variation between Early July and Early August are associated with the Rendzinas and Peats whereas consistently low concentrations of NH_4-N are associated with the Gleys (Figure 4.2 a-c). NO_3-N also varied markedly throughout the growing season among the Rendzinas, although to a lesser extent than NH_4-N, however concentrations at the beginning and end of the growing season are similar to one another (Figure 4.3a). According to the Goodwillie (1992) vegetation classification scheme RKS 2A reflected a eutrophic fertility status, RKS 5B was associated with a mesotrophic fertility status and RBS 3C, RBS 4D and RBS 4W reflected an oligotrophic condition. However, the N_t status of RBS 3C (6052 ± 58 mg l^{-1}), RBS 4D (6647 ± 723 mg l^{-1}) and RBS 4W (6721 ± 3836 mg l^{-1}) was higher than that of RKS 2A (4184 ± 465 mg l^{-1}) and RKS 5B (5158 ± 161 mg l^{-1}). There was no distinction in temporal trends of NO_3-N, NH_4-N and N_{tin} among the rendzinas in the context of the assigned contrasting trophic conditions.

Less erratic temporal variation of plant-available forms of N were associated with the Gleys than the Rendzinas with the exception of PG 5B which had a peak of NO_3-N associated with the Mid July sampling period (Figure 4.3b). PG 5B and G 9B were associated with a mesotrophic fertility status and PG 6A was associated with a more eutrophic status. Experimental plots associated with these three vegetation types had a similar N_t status (Table 4.14). An obvious distinction in temporal trends of NO_3-N, NH_4-N and N_{tin} among the Gleys in the context of the assigned contrasting fertilities was not evident.

Within the Peats, highest concentrations of NO_3-N occurred in Mid June followed by a decline in concentrations which remained less than 10 mg l^{-1} for early July to mid September (Figure 4.3c). Contrasting trends in NH_4-N temporal variation were evident among the Fen Peats and highest concentrations were associated with FP 6B (Figure 4.2c). N_t status was higher in mesotrophic FP 6B (8526 ± 648 mg l^{-1}) and PM 7B (8526 ± 1800 mg l^{-1}) than in oligotrophic PM 9C (5650 ± 460 mg l^{-1}) however, N_{tin}, NH_4-N and NO_3-N did not remain higher in both FP 6B and PM 7B than in PM 9C over the growing season (Figure 4.1c, 4.2c and 4.3c).

4.3.1.2 Phosphorus

Temporal variation in P_w over the growing season differed highly significantly among the three broad soil groups ($p \leq 0.0001$, log transformed data, Table 4.15). High degrees of temporal variation were associated with the Rendzina soil group (RBS 3C, RBS 4D, RKS 5B and RBS 4W) within which concentrations varied by an order of magnitude over the growing season (Figure 4.4a). The temporal trend associated with this soil type was exclusive to the Rendzinas. Highest values occurred in Mid May and distinctly lower values occurred consistently in the subsequent months (Figure 4.4a). The temporal variation associated with RKS 2A presents an exception to the general trend however, as maximum concentrations occurred in Mid June rather than Mid May (Figure 4.4a). The P_t status (Table 4.14) of RKS 2A (406 ± 6 mg l^{-1}), RKS 5B (354 ± 48 mg l^{-1}); RBS 3C (193 ± 7), RBS 4W (150 ± 27 mg l^{-1}), RBS 4D (200 ± 59 mg l^{-1}) reflected the contrasting fertility status of the soil types as designated by Goodwillie (1992). However, there was no distinction in temporal trends of P_w among the rendzinas in the context of the assigned contrasting trophic conditions.

Consistently low concentrations of P_w were associated with the Gleys and concentrations did not exceed 2 mg l^{-1} over the course of the growing season (Figure 4.4b). Within each Gley soil type maximum concentrations of a similar magnitude occurred during Early August in these plots (PG 6A 1.4 mg l^{-1}, G 9B 1.5 mg l^{-1} and PG 5B 1.3 mg l^{-1}). In PG 6A maximum concentrations of P_w (1.4 mg l^{-1}) during Early August were preceeded by a gradual increase whereas in G 9B and PG 5B two peaks of similar magnitude occurred during Early July and Early August (Figure 4.4b). Again, there was no obvious distinction in temporal trends of P_w among the Gleys with a contrasting trophic status.

The lowest ranges of P_w concentrations over the growing season were associated with the Peats, within which concentrations did not exceed 1 mg l^{-1} (Figure 4.4c). Within PM 7B, maximum concentrations of P_w (0.9 mg l^{-1}) occurred in Mid August preceded by a gradual increase from Early July (Figure 4.4c). Within FP 6B maximum concentrations (0.6 mg l^{-1}) also occurred during Mid August (Figure 4.4c) and had a similar temporal trend to PM 7B. Within PM 9C, the minimum and maximum concentrations ranged between 0.2-0.9 mg l^{-1}which occurred in Early July and Mid August respectively (Figure 4.4c). Again, there was no obvious distinction in temporal trends of P_w among the Peats with a contrasting trophic status.

4.3.2 Variation in mean nutrient status among sampling periods within Garryland and Knockaunroe.

4.3.2.1 Garryland

N_{tin} varied significantly among sampling periods within Garryland ($p \leq 0.001$, log transformed data, Table 4.29) and this variation differs significantly among the soil types ($p \leq 0.001$, log transformed data). Mean N_{tin} assessments generated from each sampling period ranged between 9.4 and 24.7 mgl^{-1} (Table 4.30). The highest degree of spatial variation in Nt_{in} was associated with the Mid July sampling period and the lowest degree of variation occurred in Early July (Figure 4.6). This information indicates that different degrees of spatial variation in N_{tin} occurred at different periods during the growing season. P_w also varied significantly among sampling periods ($p \leq 0.001$) and this temporal variation varied with soil type ($p \leq 0.001$). Mean P_w assessments generated from each sampling period ranged between 0.7 and 1.4 mg l^{-1} (Table 4.31). High degrees of variation were associated with the Mid June, Early July and Mid August sampling periods (Figure 4.8) and the lowest degree of variation occurred in Early August. This information indicates that different degrees of spatial variation in P_w also occurred at different periods during the growing season.

4.3.2.2 Knockaunroe

N_{tin} varied significantly among the sampling periods within Knockaunroe ($p \leq 0.001$, log transformed data, Table 4.32) and this variation differed significantly among soil types ($p \leq 0.001$, log transformed data, Table 4.32). Mean N_{tin} assessments generated from each sampling period ranged between 10.0 and 24.4 mgl^{-1} (Table 4.33). The highest degree of spatial variation in N_{tin} was associated with the Early July sampling period and the lowest degree of variation occurred in Mid September (Figure 4.10). This information indicates that different degrees of spatial variation in N_{tin} occurred at different periods during the growing season. P_w also varied significantly among sampling periods ($p \leq 0.001$, log transformed data, Table 4.32) and this temporal variation varied with soil type ($p \leq 0.01$, log transformed data, Table 4.32).

Mean P_w assessments generated from each sampling period ranged between 0.2 and 0.7 mg l^{-1} (Table 4.34) which reflect an ultra-oligotrophic condition. The highest degrees of variation occurred during the Mid June sampling period and low degrees of variation occurred during the remaining sampling periods (Figure 4.12). This information indicates that different degrees of spatial variation in P_w occurred at different periods during the growing season within Knockaunroe.

Table 4.14: Baseline soil nutrient summary statistics for each pair of experimental plots. RKS = Kilcolgan Series Rendzina; PG = Peaty Gley; RBS = Burren Series Rendzina; FP = Fen Peat; PM = Peat-marl. 2A= Lolium grassland (eutrophic); 5B = P. reptans (spp. poor) (mesotrophic); 6A = Dry C. nigra (eutrophic); 9B = E. acicularis (mesotrophic); 3C = Flooded pavement (oligotrophic); 4D = Schoenus Fen (oligotrophic); 6B = Wet C. nigra (mesotrophic); 7B = Tall Sedge (mesotrophic); 9C = Marl Pond (oligotrophic) (after Goodwillie, 1992). N/A = Data not available due to analytical oversight.

Code	Plot	Broad Soil Group	P_t mg l^{-1}	Mean±SD	N_t mg l^{-1}	Mean±SD
RKS 2A	A	Rendzina	409	405 ± 6	4512	4184 ± 465
RKS 2A	B	Rendzina	401		3855	
PG 5B	A	Gley	307	370 ± 89	5359	5294 ± 93
PG 5B	B	Gley	433		5228	
RKS 5B	A	Rendzina	388	354 ± 48	5272	5158 ± 161
RKS 5B	B	Rendzina	320		5044	
PG 6A	A	Gley	529	498 ± 45	5207	5577 ± 524
PG 6A	B	Gley	466		5947	
G 9B	A	Gley	N/A	N/A	4784	4726 ± 82
G 9B	B	Gley	N/A		4668	
RBS 3C	A	Rendzina	198	193 ± 7	6093	6052 ± 58
RBS 3C	B	Rendzina	188		6011	
RBS 4D	A	Rendzina	158	200 ± 59	6135	6647 ± 723
RBS 4D	B	Rendzina	241		7158	
FP 6B	A	Peat	261	269 ± 11	8068	8526 ± 648
FP 6B	B	Peat	276		8984	
PM 7B	A	Peat	219	181 ± 55	9798	8526 ± 1800
PM 7B	B	Peat	142		7253	
RBS 4W	A	Rendzina	170	150 ± 27	9433	6721 ± 3836
RBS 4W	B	Rendzina	132		4009	
PM 9C	A	Peat	185	159 ± 38	5975	5650 ± 460
PM 9C	B	Peat	132		5324	

Table 4.15: Repeated measures analysis of variance summary for comparison of temporal trends in N_{tin}, NO_3-N, NH_4-N and P_w among turlough Rendzinas, Gleys and Peats.

	Source of variation								
	Soil Type			Sampling period			Soil Type*Sampling period		
Variable	*df*	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
NH_4-N	2	54.58	≤0.0001	6	1.80	0.1007	11	10.04	≤0.0001
NO_3-N	2	5.58	0.0124	6	11.12	≤0.0001	11	4.48	≤0.0001
N_{tin}	2	1.19	0.3232	6	2.45	0.0296	11	1.08	0.3856
P_w	2	0.65	0.5317	6	14.10	≤0.0001	11	7.33	≤0.0001

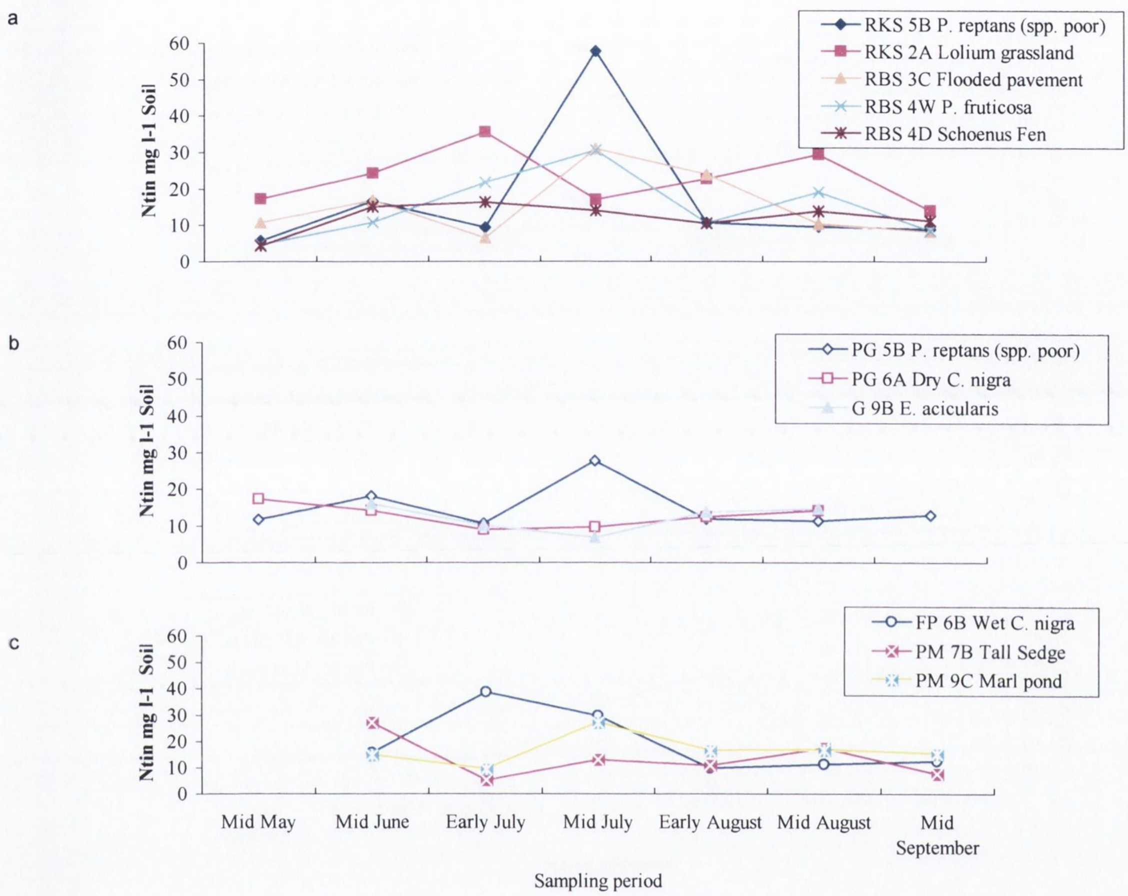

Figure 4.1 (a-c): Variation in temporal trends of N_{tin} soil concentrations among turlough Rendzinas, Gleys and Peats (RKS = Rendzina, Kilcolgan Series; RBS = Rendzina, Burren Series; PG = Peaty Gley; G = Gley; FP = Fen Peat; PM = Peat-Marl) associated with different vegetation types. Data are the mean of two experimental plots. Data are the mean of two experimental plots.

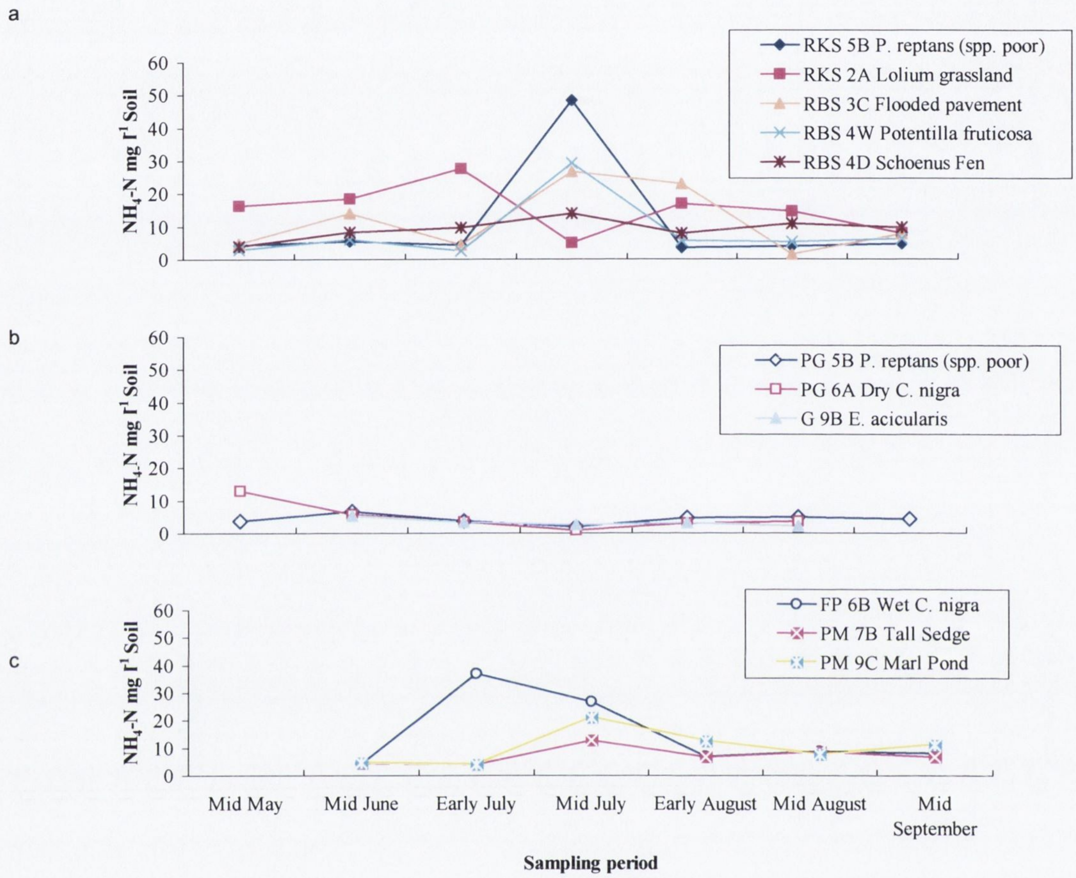

Figure 4.2 (a-c): Variation in temporal trends of NH_4-N soil concentrations among turlough Rendzinas, Gleys and Peats (RKS = Rendzina, Kilcolgan Series; RBS = Rendzina, Burren Series; PG = Peaty Gley; G = Gley; FP = Fen Peat; PM = Peat-Marl) associated with different vegetation types. Data are the mean of two experimental plots.

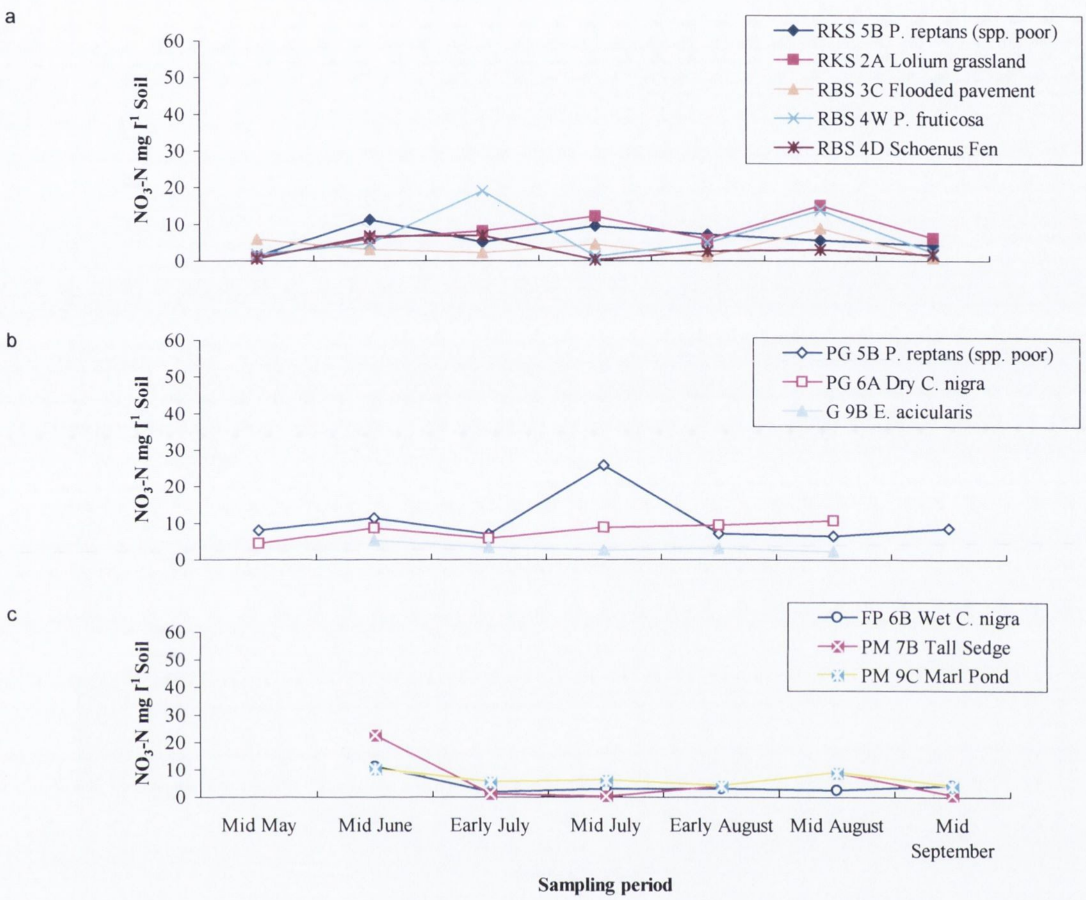

Figure 4.3 (a-c): Variation in temporal trends of NO_3-N soil concentrations among turlough Rendzinas, Gleys and Peats (RKS = Rendzina, Kilcolgan Series; RBS = Rendzina, Burren Series; PG = Peaty Gley; G = Gley; FP = Fen Peat; PM = Peat-Marl) associated with different vegetation types. Data are the mean of two experimental plots.

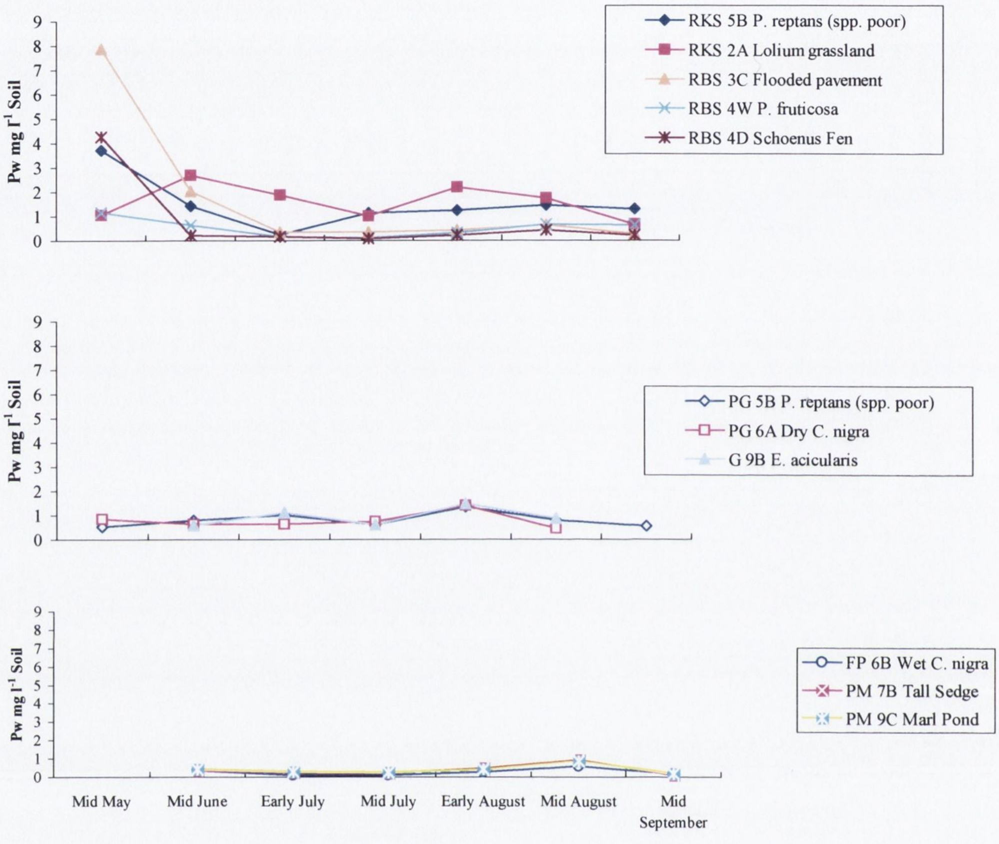

Figure 4.4 (a-c): Varitation in temporal trends of P_w soil concentrations among turlough Rendzinas, Gleys and Peats (RKS = Rendzina, Kilcolgan Series; RBS = Rendzina, Burren Series; PG = Peaty Gley; G = Gley; FP = Fen Peat; PM = Peat-Marl) associated with different vegetation types. Data are the mean of two experimental plots.

Table 4.18: Summary of temporal variation in soil properties and nutrient status within Kilcolgan Series Rendzina (Lolium Grassland) (KSR 2A) in Caherglassaun Turlough, Co. Galway (Coole-Garryland catchment) over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	5.6	15.9	29.2	7.7	15.1	22.8	1.6
SD	0.2	5.4	6.6	4.6	7.3	7.6	0.7
Min	5.5	11.8	24.4	0.8	4.9	14.0	1.1
Max	5.9	26.6	42.9	14.9	27.4	35.4	2.6

Table 4.19: Summary of temporal variation in soil properties and nutrient status within Peaty Gley (*Potentilla reptans* spp. poor) (PG 5B) in Coole Turlough, Co. Galway (Coole-Garryland catchment over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	6.04	23.4	36.9	10.6	4.3	14.9	0.8
SD	0.1	7.0	3.2	6.9	1.4	6.2	0.3
Min	5.9	14.7	31.3	5.7	1.9	5.7	0.5
Max	6.2	31.4	40.6	23.3	6.2	23.3	1.3

Table 4.20: Summary of temporal variation in soil properties and nutrient status within Kilcolgan Series Rendzina (*Potentilla reptans* spp. poor) (KSR 5B) in Garryland Turlough, Co. Galway (Coole-Garryland catchment) over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	6.0	22.2	39.0	6.2	10.6	16.9	1.5
SD	0.04	0.7	4.3	3.3	16.6	18.3	1.1
Min	6.0	21.7	32.9	4.2	3.9	5.6	0.3
Max	6.1	23.2	45.5	10.5	47.3	57.7	3.8

Table 4.21: Summary of temporal variation in soil properties and nutrient status within Peaty Gley (Dry *Carex nigra*) (PG 6A) in Garryland Turlough, Co. Galway (Coole-Garryland catchment) over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	6.4	28.3	51.2	7.9	4.8	12.7	0.8
SD	0.19	2.6	1.6	2.4	4.2	3.1	0.3
Min	6.3	25.0	49.0	4.4	0.8	8.9	0.6
Max	6.7	31.9	53	10.6	12.9	14.1	1.4

Table 4.22: Summary of temporal variation in soil properties and nutrient status within Gley (*Eleocharis acicularis*) (G 9B) in Garryland Turlough, Co. Galway (Coole-Garryland catchment) over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	6.5	16.4	46.8	9.0	3.3	12.3	0.9
SD	0.18	4.8	7.5	3.4	1.1	3.8	0.4
Min	6.3	12.5	37.0	4.2	2.6	6.8	0.6
Max	6.8	15.1	56.0	12.5	5.2	16.1	1.5

Table 4.23: Summary of temporal variation in soil properties and nutrient status within Burren Series Rendzina (*Potentilla fruticosa*) (BSR 4W) in Knockaunroe Turlough, Co. Clare (East Burren catchment) over the 2004 growing season.

	pH	OM	SM	NO_3-N	NH_4-N	N_{tin}	P_w
Mean	7.11	39.1	51.9	6.8	8.3	15.1	0.5
SD	0.16	12.0	1.4	6.8	9.4	9.0	0.4
Min	7.0	14.4	51	1.2	2.9	4.6	0.1
Max	7.4	47.8	54	13.8	29.3	30.5	1.2

Table 4.24: Summary of temporal variation in soil properties and nutrient status within Burren Series Rendzina (Flooded pavement) (BSR 3C) in Knockaunroe Turlough, Co. Clare (East Burren catchment) over the 2004 growing season.

	pH	OM	SM	NO_3-N	NH_4-N	N_{tin}	P_w
Mean	6.5	24.0	40.7	3.7	11.6	15.3	1.7
SD	0.5	4.8	2.9	2.9	9.8	9.1	2.8
Min	6.0	20.4	36	0.9	4.8	6.4	0.3
Max	7.4	33.4	45	5.7	31.4	30.9	7.6

Table 4.25: Summary of temporal variation in soil properties and nutrient status within Burren Series Rendzina (Schoenus Fen) (BSR 4D) in Knockaunroe Turlough, Co. Clare (East Burren catchment) over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	7.8	43.9	57.6	3.0	9.1	12.1	0.8
SD	0.15	7.5	3.4	2.7	3.0	4.0	1.5
Min	7.5	39.1	54.0	0.2	3.8	4.3	0.1
Max	8.0	59.7	63.0	6.8	13.8	13.9	4.3

Table 4.26: Summary of temporal variation in soil properties and nutrient status within Fen Peat (Wet *Carex nigra*) (FP 6B) in Knockaunroe Turlough, Co. Clare (East Burren catchment) over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	7.7	49.3	76.5	4.2	15.2	19.5	0.3
SD	0.2	15.2	4.4	3.4	13.3	11.8	0.2
Min	7.4	28.2	70.1	1.8	4.1	9.8	0.1
Max	7.8	64.8	79.6	11.1	36.7	38.6	0.6

Table 4.27: Summary of temporal variation in soil properties and nutrient status within Peat marl (Tall Sedge) (PM 7B) in Knockaunroe Turlough, Co. Clare (East Burren catchment) over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	7.9	49.3	64.2	6.2	7.2	13.4	0.4
SD	0.3	15.2	5.1	8.6	3.2	7.9	0.3
Min	7.6	28.2	59.0	0.2	3.9	5.2	0.1
Max	8.2	64.8	73.0	22.5	12.7	27	0.9

Table 4.28: Summary of temporal variation in soil properties and nutrient status within Peat marl (Marl Pond) (PM 9C) in Knockaunroe Turlough, Co. Clare (East Burren catchment) over the 2004 growing season.

	pH	%OM	%SM	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}	N_{tin} mg l^{-1}	P_w mg l^{-1}
Mean	8.4	20.8	52.8	6.4	10.2	16.5	0.4
SD	0.1	2.1	1.2	2.6	6.3	5.8	0.3
Min	8.2	19.0	52.0	4.0	3.8	9.2	0.2
Max	8.8	23.4	63.0	10.1	21.0	27	0.9

Table 4.29: Repeated measures analysis of variance summary of comparison of temporal trends in nutrient availability within Garryland.

	Source of variation								
	Soil /Vegetation Type			Sampling period			Soil /Vegetation Type *Sampling period		
Variable	*df*	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
LNt_{in}	2	7.936	0.0634	4	9.6804	0.0010	8	23.731	$\leq$0.0001
P_w	2	1.2317	0.4069	4	6.7037	0.0003	8	4.843	0.0003

Table 4.30: Summary of N_{tin} (mg l^{-1} Soil) variation within Garryland at each sampling period.

	Mid June	Early July	Mid July	Early August	Mid August
Mean	15.6	9.4	24.7	12.2	12.8
SD	1.3	0.5	28.6	1.6	2.8
Min	14.1	8.9	6.8	10.6	9.5
Max	16.6	10.0	57.7	13.8	14.7

Table 4.31: Summary of P_w (mg l^{-1} Soil) variation within Garryland at each sampling period.

	Mid June	Early July	Mid July	Early August	Mid August
Mean	0.9	0.7	0.8	1.4	0.9
SD	0.5	0.4	0.3	0.1	0.5
Min	0.6	0.3	0.6	1.3	0.5
Max	1.4	1.1	1.1	1.5	1.5

Table 4.32: Repeated measures analysis of variance summary of comparison of temporal trends in nutrient availability within Knockaunroe.

	Source of variation								
	Soil/Vegetation Type			Sampling period			Soil/Vegetation Type *Sampling period		
Variable	*df*	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
LNt_{in}	5	1.2883	0.3783	5	6.662	0.0003	25	3.6551	0.0005
LP_w	5	9.4883	0.0081	5	30.848	$\leq$0.0001	25	1.9204	0.0124

Table 4.33: Summary of N_{tin} (mg l^{-1} Soil) variation within Knockaunroe at each sampling period.

	Mid June	Early July	Mid July	Early August	Mid August	Mid Sept
Mean	16.6	16.2	24.4	13.3	14.5	10.0
SD	5.5	12.7	8.5	5.4	3.5	2.3
Min	14.4	5.2	12.9	9.8	10.2	7.5
Max	26.9	38.6	30.9	23.8	19.1	12.7

Table 4.34: Summary of P_w (mg l^{-1} Soil) variation within Knockaunroe at each sampling period.

	Mid June	Early July	Mid July	Early August	Mid August	Mid Sept
Mean	0.7	0.2	0.2	0.4	0.7	0.7
SD	0.7	0.1	0.1	0.1	0.2	0.2
Min	0.2	0.1	0.1	0.2	0.4	0.4
Max	2.0	0.3	0.4	0.5	0.9	0.9

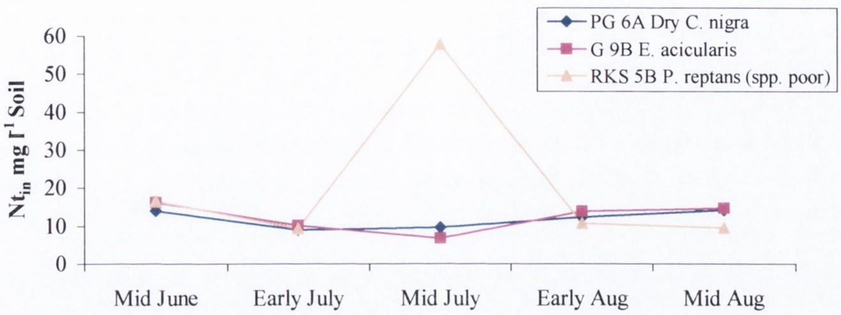

Figure 4.5: Variation in temporal trends of N_{tin} among soil types associated with different vegetation types within Garryland turlough, Coole Garryland catchment. Data are the mean of two experimental plots.

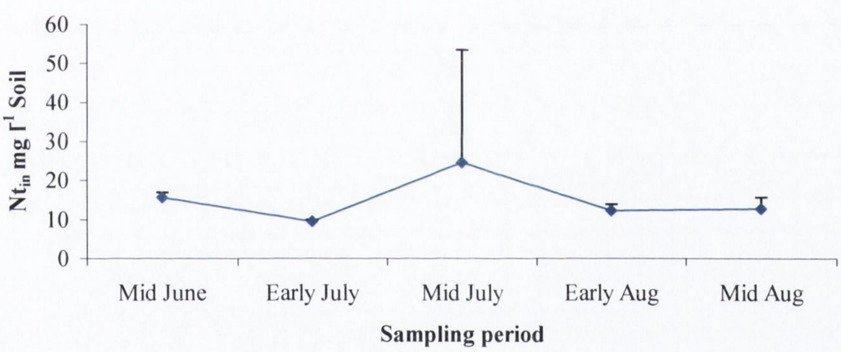

Figure 4.6: Variation in mean N_{tin} status among sampling periods within Garryland, Coole Garryland catchment. Values are the mean ± SD of seven pairs of experimental plots.

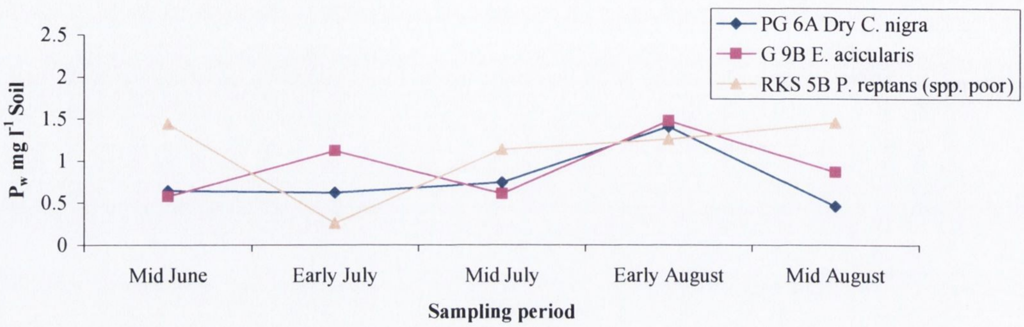

Figure 4.7: Variation in temporal trends of P_w among soil types associated with different vegetation types within Garryland turlough, Coole Garryland catchment. Data are the mean of two experimental plots.

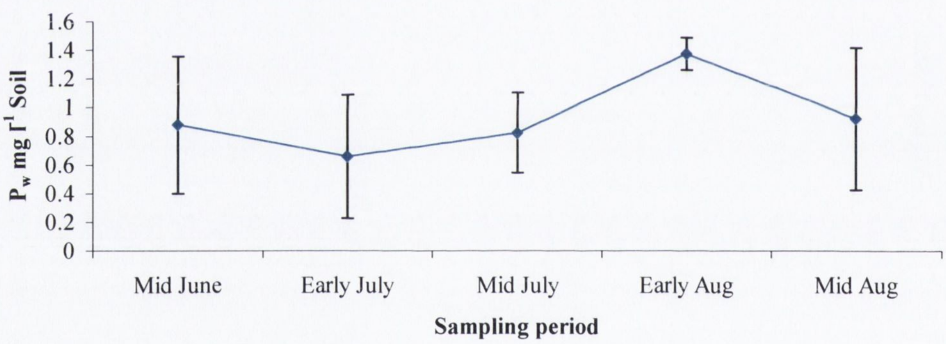

Figure 4.8: Variation in mean P_w status among sampling periods within Garryland, Coole Garryland catchment. Values are the mean ± SD of seven pairs of experimental plots.

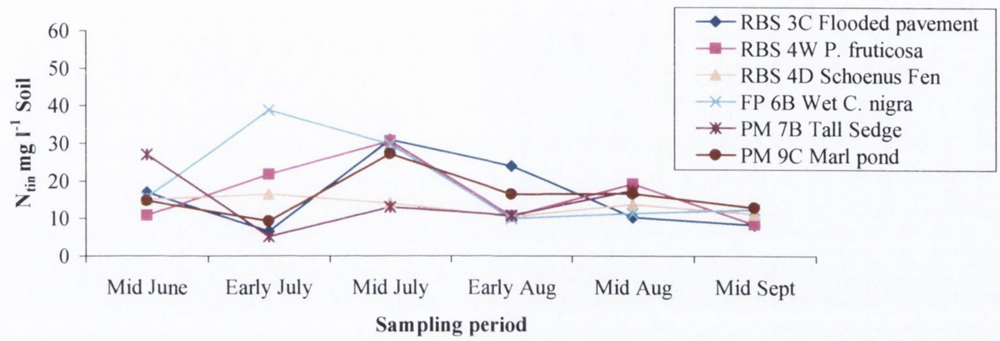

Figure 4.9: Variation in temporal trends of N_{tin} among soil types associated with different vegetation types within Knockaunroe turlough, East Burren catchment. Data are the mean of two experimental plots.

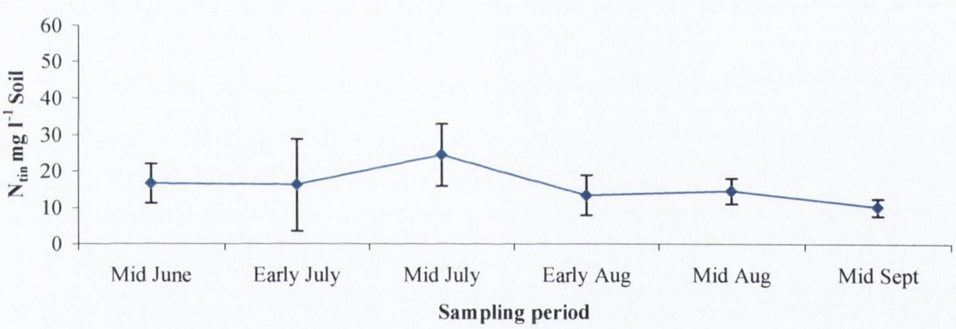

Figure 4.10: Variation in mean N_{tin} status among sampling periods within Knockaunroe turlough, East Burren catchment. Values are the mean ± SD of seven pairs of experimental plots.

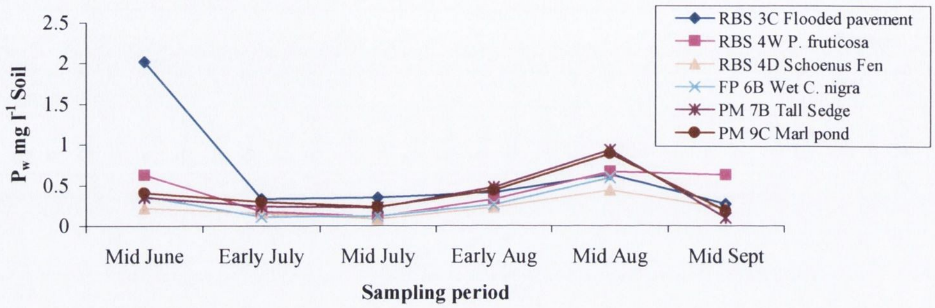

Figure 4.11: Variation in temporal trends of P_w among soil types associated with different vegetation types within Knockaunroe turlough, East Burren catchment. Data are the mean of two experimental plots.

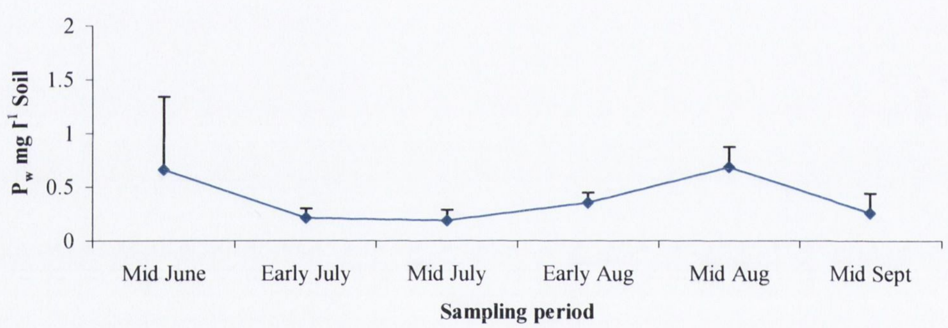

Figure 4.12: Variation in mean P_w status among sampling periods within Knockaunroe turlough, East Burren catchment. Values are the mean ± SD of seven pairs of experimental plots.

4.4 Discussion

4.4.1 Variation in temporal trends of plant-nutrient availability among turlough soil types

The variation of N_{tin}, NH_4-N and NO_3-N within and among the broad soil groups suggest that turlough soil nitrogen dynamics are highly complex. Temporal trends of N_{tin} did not differ among the soil groups. However, temporal trends of the different forms of plant-available N (NH_4-N and NO_3-N) varied among the Rendzinas, Gleys and Peats. Generally, NH_4-N was the dominant form of plant-available N within the Rendzinas. However, these soils were characterised by erratic temporal variations of plant-available N and rapid shifts from NH_4-N to NO_3-N dominance. Similar erratic temporal shifts in NH_4-N were not associated with the Gleys within which concentrations remained low and sTable over the course of the growing season. Temporal variations of NO_3-N were marginally more dynamic than those of NH_4-N and generally NO_3-N dominance was associated with the Gleys. Similar temporal trends in NO_3-N variations occurred among the Peats in tandem with comparatively more erractic NH_4-N trends.

There is a limited amount of comparable information on temporal trends in N availability in the literature which impairs conclusive insight. However, a relevant study was conducted by Davy and Taylor (1974) on annual soil nitrogen dynamics in three contrasting soil types (chalk, calcimorphic brown earth and acid mull) to characterise the nitrogen regimes under which *Deschampsia caespitosa* is able to maintain dominance of vegetation. Davy and Taylor (1974) reported that at the time of each monthly sampling period the quantity of NH_4-N generally exceeded that of NO_3-N in all three soils and that seasonal changes tended to run in parallel within the three soils. These authors also determined monthly N mineralization rates and highlighted the inadequacy of NO_3-N and NH_4-N concentrations alone for assessing soil nitrogen status. In order to facilitate a comparison between the results obtained by Davy and Taylor (1974) and the results observed in this study, focus was placed on the temporal change in both forms of inorganic N from spring to summer. In the chalk soils NO_3-N and NH_4-N had consistently similar concentrations throughout this period, NH_4-N concentrations varied markedly over time in the calcimorphic brown earth, and in the acid mull NH_4-N remained consistently higher than NO_3-N by an order of magnitude. Davy and Taylor (1974) reported that highest potential mineralization rates are associated with the summer period and they found links between these rates and soil nitrogen status. High mineralisation rates may account for the high NH_4-N concentrations recorded in the Rendzinas and Peats during the mid-summer period. Davy and Taylor (1974) reported that low concentrations of mineral N in March and April were thought to indicate that rates of uptake by plants were exceeding the rapidly increasing mineralization rates at this time.

The peaks of mineral N at the end of May reflected rapid mineralization during the immediately preceding period while the declines until September resulted from the decreasing mineralization rate (Davy and Taylor, 1974). The high values of NH_4-N and rapid shifts from NH_4-N to NO_3-N dominance associated with sampling periods from Early July to Mid August are possibly related to rapid rates of mineralization and nitrification associated with the turlough Rendzinas. The fact that NO_3-N concentrations account for the majority of mineral-N in the Gleys suggests that mineralization rates are less rapid than within the Rendzinas or possibly any NH_4-N is rapidly converted to NO_3-N due to high levels of nitrification. The N dynamics associated with the Peats suggest that nitrification may be inhibited as NH_4-N consistently exceeds NO_3-N which remains extremely low and peaks in NO_3-N do not occur following peaks in NH_4-N. The contrasting trends in mineral N among the three soil types may also result from a higher degree of grazing in the upper areas of turloughs where Rendzinas dominate, as personal observation suggests that animals tend to avoid the deeper unsTable Gleys and Peats in lower turlough areas or preferentially browse taller, more palaTable grass/forb dominated swards in the upper turlough areas. Davy and Taylor (1974) also suggest that soil water content and specifically soil desiccation may have affected the seasonal pattern they observed in N mineralization. During their studies, June to September corresponded with drier soil samples, which had water contents ranging from 14.3-50%, and water deficit is likely to have restricted microbial activity. Soil moisture content remained below 50% in RKS 2A, PG 5B, RKS 5B and RBS 3C but water content as a percentage of dry weight is not very useful as an indicator of soil desiccation unless the permanent wilting point and field capacity are known, because a water content representing field capacity in one soil might be below the wilting point in another (Kramer and Boyer, 1995). The highest range of soil moisture was associated with the Peats and potential inhibition of nitrification within these soils may be the result of high soil moisture contents. Several studies have demonstrated that N availability is tightly coupled to soil organic matter dynamics (Pastor *et al.,* 1987; Zak *et al.,* 1990) as mineralization rates are generally slow where disturbance had reduced soil organic matter content. Of the ecosystems studied by Zak and Grigal (1991) the swamp forest exhibited the lowest rates of absolute and relative mineralization even though this system had the lowest C:N ratio (14). N availability in this ecosystem is probably more limited by seasonal inundation and anaerobic conditions than by organic matter quality. This information highlights the fact that understanding variation in the different forms of mineral N is an important aspect of elucidating temporal variation in N dynamics.

Davy and Taylor (1974) reported that the concentrations of nitrogen within each of the soils observed over the course of the year remained below < 15mg l^{-1} and were classified by the authors as low in terms of their nitrogen fertility. The turlough soils studied have a similarly low range and generally remain below 20 mgl^{-1} reflecting a more low-intermediate N fertility status which is in general agreement with Ellenberg Scores. However, the lack of clear distinctions in nitrogen fertility among soils with an assumed contrasting trophic status suggests that Ellenberg scores for turlough trophic assessment should not be used in lieu of soil nutrient assessment and that a reappraisal of the use of Ellenberg Fertility Scores for turlough trophic assessments is required. Soil N dynamics are complex and future research should focus on N flux through soil organic matter using long term decomposition field experiments, with particular attention being given to mineralisation processes.

Further studies aimed at quantifying nitrate leaching and groundwater transport, in combination with my results, could provide a more complete understanding of the link between N availability and loss among these systems. Seasonal changes in climate would be expected to have an important influence on, among other things, the size, composition and activity of soil microbial populations as well as the quantity and quality of organic matter available as a substrate. As noted in Taylor *et al.* (1982), these factors would give rise to periodicity in nitrogen mineralization. There is generally an annual cycle of net mineral nitrogen production, with one or more peaks as has been shown by studies of woodland soils, wet fertilised meadow soils and semi-natural grassland (Taylor *et al.,* 1982). Thus the characterisation and comparison of different soil types with respect to nitrogen mineralisation could be adequately achieved only on a temporal basis.

P_w concentrations in the turlough soils studied consistently reflect an oligotrophic and ultra-oligotrophic condition and suggest that P is potentially limiting plant growth within numerous vegetation types. The higher degree of variation in P_w associated with the Rendzinas in comparison to the Gleys and Peats suggests that comparing the P status of Rendzinas with other turlough soil types may present a greater challenge. P_w was found to range between 1.3 and 24.2 mg l^{-1} across eleven soil associations representing important Irish agricultural grassland soils (Daly *et al.,* 2001). The analyses in the study were conducted on dried soils however, and numerous studies have shown that P_w analyses conducted on dried soils yield higher concentrations than analyses conducted on moist soils (e.g. Turner and Haygarth, 2001; Styles *et al.* 2004). Styles (2004) investigated the effect of drying soil samples, and consequences for comparing P dynamics between soils and seasons, on common soil associations in the Mask catchment and mean water-extracTable P in moist samples did not exceed approximately 5 mg l^{-1}.

In the present study the majority of P_w concentrations observed over the growing season within each soil type/vegetation type were below 2 mg l^{-1} and reflected an oligotrophic situation. Vegetation communities associated with Rendzinas, Gleys and Peats would be expected to experience contrasting fluxes in the forms of plant-available N and P which would be expected to competitively favour species which can adapt to such variations, particularly within the Rendzinas.

4.4.2 Implications of temporal variation in nutrient status for soil nutrient assessment of individual turloughs.

Temporal trends in N_{tin} differed among the Garryland Rendzinas and Gleys due to a peak of N_{tin} concentrations associated with the Rendzinas in July. This peak may be attributed to animal inputs as the upper level Rendzinas were heavily grazed by cattle and sheep within this turlough. Concentrations of N_{tin} varied significantly among the sampling periods in Garryland and mean nutrient assessments reflected either a low (< 15 mg l^{-1}) or medium (15-30 mg l^{-1}) fertility status. Mean N_{tin} assessments in Mid June, Early July, Early August and Mid August indicated a low nitrogen fertility assessment, whereas an intermediate fertility assessment was determined in the Mid June sampling period which was associated with the highest degree of variation. Temporal trends of P_w did not vary among the spatially distinct Rendzinas and Gleys but mean P_w status of Garryland differed among the sampling periods. However, this difference was ecologically insignificant as all P_w mean assessments reflected an oligotrophic condition. Mean P_w concentrations in Garryland reflected an oligotrophic condition and did not reflect the higher background P status in comparison to Knockaunroe. P_t concentrations of national agricultural grassland soils range from 193 to 1553 mgl^{-1} with a mean of 664 mgl^{-1} (Daly *et al.*, 2001) and P_t concentrations observed in Garryland were towards the low end of the range. Precipitation of phosphorus occurs with iron and aluminium in soils with a pH below 6.5 (Tisdale *et al.,* 1990). Soil pH in Garryland generally remained below 6.5 throughout the growing season and the high Fe concentrations associated with this turlough (Chapters 2. and 3.) indicate that iron oxides may be rapidly adsorbing phosphorus and reducing P availability. Sustained P cycling through an active decomposer population, regulated by microbial/faunal interactions (Ingham *et al.,* 1985) is considered essential for maintaining soil fertility. Tate *et al.* (1991a) found that in low fertility soils the relatively small fluctuations in inorganic P compared to those in the high fertility soil suggest that P cycles more slowly through the microbial biomass.

Temporal trends in N_{tin} did not vary among the soil types and associated vegetation types representative of both upper and lower levels in Knockaunroe (indicative of oligotrophic and mesotrophic conditions according to Goodwillie (1992). Mean N_{tin} assessments did vary among sampling periods and indicated an intermediate fertility status in Mid June, Early July and Mid July and a low fertility status in Early August, Mid August and Mid September. The nutrient assessments associated with the Early July and Mid July sampling periods however were characterised by a high degree of spatial variation. P_w differed among the sampling periods within Knockaunroe, however the mean concentrations determined at each sampling period reflected an ultra-oligotrophic condition in P fertility as concentrations of P_w are consistently below the minimum (1.3 mg l^{-1}) recorded for grassland soils in Ireland (Daly *et al.,* 2001). Each of the experimental plots had a pH of greater that 7.0. As pH increases above 7.0 calcium forms Ca-P compounds that precipitate phosphorus and adsorbs P (Tisdale *et al.,* 1990) and these factors may be limiting the availability of P in this turlough throughout the growing season.

4.5 Conclusions

The main findings of work presented in this chapter are:

- Temporal trends in plant-available forms of N and P differed among the Rendzinas, Gleys and Peats, which suggests that contrasting nutrient cycling dynamics are associated with these different soil types.
- Turlough rendzinas exhibited the greatest degree of variation in plant-available N and rapid shifts from NH_4-N to NO_3-N over the growing season. Greatest degrees of variation in P_w were also associated with the Rendzinas. Due to their very shallow nature, in contrast to the Gleys and Peats, the Rendzinas would be expected to experience extreme wetting and drying cycles which may influence soil N and P dynamics. Soil N dynamics associated with Rendzinas were also likely to be influenced by animal inputs more than the Gleys and Peats, as the Rendzina plots were located in upper, less frequently flooded turlough areas and presented a more sTable substrate and more palaTable vegetation for grazing.
- The extremely low plant-available P status associated with the three soil types over the growing season suggests that P may generally be limiting turlough productivity.
- No clear distinction in temporal trends of plant available N and P was evident among soils associated with vegetation types indicative of different trophic status. Temporal trends reflect an ultra-oligotrophic to mesotrophic status and further research is required to determine turlough soil trophic categories at the landscape-scale based on soil nutrient studies rather than on assessments purely based on vegetation types.
- Temporal trends of N_{tin} within Garryland and Knockaunroe suggested that spatial variation in nutrient status was more pronounced at particular points of the growing season, particularly during the mid-summer months when rapid rates of mineralization and plant nutrient uptake were likely to be occurring. These temporal trends influenced the mean trophic assessments of both turloughs. P_w assessments were more temporally sTable and may provide a more useful trophic assessment. Mean nutrient assessments based on P_w consistently reflected an oligotrophic and ultra-oligotrophic nutrient status within Garryland and Knockaunroe respectively.

CHAPTER 5. OVERALL CONCLUSIONS AND RECOMMENDATIONS

The lists of specific aims listed in sections 2.1, 3.1 and 4.1 have been addressed in the bulletted conclusions at the end of each chapter. This short, final chapter aims to synthesise the main findings from each chapter and to provide recommendations for future turlough soil research.

5. 1 Turlough soil types and nutrient status

5.1.1 Summary of main findings

Turloughs associated with both catchments were found to vary in the general nature of their soil types. Mineral, moderately calcareous soils were associated with Coole Garryland whereas highly organic, highly calcareous soils were associated with the East Burren. This variation in soil types was attributed to the contrasting parent materials, hydrology and hydrochemistry associated with the different types of karst aquifers within each catchment area. The general N, P and K status of the two catchments was low, which is in agreement with previous trophic assessments of turloughs as low nutrient habitats which are sensitive to enrichment. A higher total nitrogen status was associated with the East Burren catchment, which is likely to be linked to the high organic matter associated with this catchment, resulting in nitrogen accumulation. Assessments of plant-available forms of nitrogen along the flooding gradients of turloughs representative of both catchments also reflected an oligotrophic condition. However, plant-available forms of N were generally lower in East Burren than in Coole Garryland. Marginally higher (total and available) phosphorus and potassium concentrations were associated with Coole Garryland. Investigations of plant available N and P temporal trends within two turloughs characteristic of each catchment (Knockaunroe and Garryland) revealed that these nutrients remained low, and are potentially limiting growth, over the course of the growing seaon. At the within-turlough scale there were no obvious relationships between the temporal trends of plant-available N and P and associated vegetation types indicative of a range of different trophic conditions (oligotrophic, mesotrophic and eutrophic). These results highlight the challenges for making meaningful assessments of soil trophic status within these low nutrient habitats.

The different soil types and hydrological and hydrochemical conditions associated with both catchments are likely to induce different soil nutrient cycling rates within their associated turloughs. Turloughs in Coole Garryland are likely to be more intensively managed than turloughs in the East Burren, however, and a combination of management and karst aquifer factors are likely to drive variations in nutrient status between the catchment areas. The integrated influence of karst and management factors on turlough soil nutrient conditions may also influence the vegetation types associated with different soil types.

One of the main limitations of this thesis is the lack of systematically collected management data and future studies on turlough ecology should incorporate management assessments.

Soil nutrient conditions are thought to be a secondary influence to flooding on the distributions of grass/forb dominated vegetation types and sedge dominated vegetation types. Degrees of wetness and associated soil alkalinities were determined as the primary influences on the distribution of these two broad, commonly occuring vegetation types within and among turloughs. There is an intrinsic link therefore between vegetation types and soil types, the development of which are highly influenced by hydrological and hydrochemical factors. The relationships between turlough vegetation types and soil types are less related to the nutrient status of the soil types but are more associated with their moisture regimes and alkalinities. Turloughs, and areas of turloughs, with grass and forb dominated vegetation communities on mineral soil types are likely to be more intensively managed than those with sedge dominated communities associated with peat, marl and peat-marl due to the less palaTable nature of the plant species and more unsTable substrates. The influences on turlough soil nutrient status are many and varied. However, future studies focussing on the broad patterns of associations between soil types, vegetation types and management factors should provide the key to understanding turlough ecology.

5.1.2 Recommendations for future research

Future turlough soil nutrient research should focus on integrated catchment-scale and within turlough scale studies. Catchment-scale studies should focus on the relationships between karst aquifers, soil types, vegetation types and management factors on a wide range of turloughs currently designated as SACs. Turlough catchments should refer to the zone of groundwater contributing to the turlough and integrated studies are required to fuse expertise in groundwater delineation, soil surveys, vegetation descriptions and within-turlough and catchment based management assessments. Based on the results presented in this thesis, it is anticipated that different types of karst aquifers are associated with specific ranges of soil types, vegetation types and levels of within-site and catchment based management. If this proves to be the case, turloughs under high degrees of management pressure could be identifed and appropriate management recommendations for these different degrees of pressures could be formulated.

Within-turlough scale soil nutrient studies should focus on improving understanding of the factors influencing nutrient cycling rates and nutrient limitation within and among turloughs. Coordinated studies on N, P and K should be conducted at a limited number of long-term research sites for which hydrological, hydrochemical and vegetation information are also available.

There should be a diverse range of managements both within and among such sites to allow for assessments of the impact of management on soil nutrient dynamics. Ideally, such research sites should be selected by all stakeholders associated with turloughs to promote integrated, coordinated research. A general debate on turlough trophic status is also required. Focus should be placed on gathering quantitative nutrient data, representative of the aquatic and terrestrial phases of the habitat, to refine trophic categories relevant to turloughs.

Nutrient cycling investigations should focus on the N mineralisation/nitrification rates and P sorption/desorption dynamics of different common soil types, which would address the issue of the capacities of turlough soils to retain and supply nutrients. Nutrient limitation studies are best conducted by factorial fertiliser experiments. The response of turlough vegetation communities to applications of N, P or K based fertilisers would improve understanding of the relative controls exerted by these major plant nutrients on plant productivity within turloughs.

Quantifying the inter-relationships between floodwater quality and soil nutrient status presents one of the major issues for generating an improved understanding of turlough ecological functions at the catchment scale. Elucidating relationships between turlough water quality and soil nutrient status should be researched at the broad scale by investigating associations between mean assessments of soil and floodwater nutrients across numerous turloughs. Attempts to quantify the potential for soil nutrient release to the water column should initially be conducted by controlled, laboratory based experiments using soils from the selected long-term research sites. These investigations would improve understanding of the catchment-scale ecological functions of turloughs, such as whether they are potential sinks or sources of nutrients to groundwater. Future turlough soil spatial research should focus on turlough soil property heterogeneity within the limited number of long-term research sites. Ettema and Wardle (2002) provide a useful summary of the application of geostatistics to spatial soil ecology. Nutrient heterogeneity (patchiness) refers to variability which has spatial structure. By quantifying its patterns and scales, the controls and consequences of heterogeneity can be assessed. For soil properties heterogeneity is most often quantified using geostatistics, because of its robust characteristics and mapping capabilities Detecting spatial pattern is highly dependent on the soil property studied, the characteristics of the study area and spacing of samples. Attempts to quantify soil property spatial dependence within individual turloughs should, in my opinion, focus on the major plant nutrients (N, P and K) and soil type characteristics (soil depth, pH, OM) at the scale related to the distribution of plant communities. Within each of the limited number of turlough research sites, samples could be collected along 200 m transects at 5 m intervals. The application of geostatistics to this information would provide comparable information on soil property heterogeneity within different turloughs.

5.2 Challenges for turlough soil nutrient assessments

5.2.1 Summary of main findings

Assessments of turlough trophic status should take both the aquatic and terrestrial phases of the habitat into account. The terrestrial phase assessments will need to produce meaningful and comparable soil nutrient assessments for turloughs with different areas, depths and topographies. The results presented in this thesis suggest that the spatial and temporal fluxes of nutrients in turlough soils present challenges for making accurate soil nutrient assessments. Variations in nutrient status among turloughs associated with both catchments were often dependent on sampling location. This highlights the requirement for sampling strategies which cover the range of variation within the turlough basin. Soil type variations along the flooding gradients of turloughs within each catchment had both similar and contrasting elements and these differences in soil types, particularly among the lower elevations, emphasise the need for individual turlough soil type surveys. High degrees of variation in plant-nutrient availability were associated with the turlough flooding gradients and spatial patterns were not obviously linked to soil type. Soil moisture conditions at the time of sampling are likely to greatly influence soil nutrient status at any given location in a turlough, particularly in the lower turlough areas. Different soil properties varied to different extents within turloughs with the same typology, indicating that accurate soil nutrient assessments will be more readily estimated for some soil nutrient properties than others. Investigations of nutrient property variations within and among soil types showed that soil properties varied to different extents within different soil types. The high degrees of variation associated with the soil types highlight the necessity for adequate sub-sampling within soil types when conducting soil nutrient assessments based on soil type maps. Temporal trends in nutrient availability also varied among soil types. Temporal trends of plant-available N and P were more erratic within the Rendzinas in comparison to Gleys and Peats and such temporal variability has a greater implication for obtaining representative soil nutrient assessments of these characteristically shallow soil types. Higher degrees of variation in the different forms of plant-available N were associated with the mid-summer sampling period. However, this was not the case for temporal variations in plant-available P, which were relatively sTable. Investigations of the implications of temporal variation for the soil nutrient assessments of two turloughs (Garryland and Knockaunroe) showed that mean N and P status varied among sampling periods, but mean assessments consistently reflected an oligotrophic and ultra-oligotrophic status respectively.

5.2.2 Recommendations for turlough soil nutrient assessments

To aid turlough soil nutrient assessments, focus should initially be placed on improving soil type classification and attempts should be made to classify turlough soils to the soil series level. Producing soil type maps for turloughs designated as SACs should be a priority, as sampling strategies for nutrient assessments are best conducted with a prior knowledge of the soil types present at a site. In the absence of soil maps, soil morphology descriptions should accompany soil sampling for nutrient analysis. Further attempts to relate soil types, classified to the Series level, to soil nutrient status should then be a priority. The goals of any potential turlough soil survey, and the associated time constraints and resources, should drive the sampling strategies and preliminary site investigations. If the goal is to produce soil nutrient assessments of numerous turloughs using limited resources, a preliminary site assessment of the main topographical variations and vegetation communities should be conducted within each turlough and broad soil groups should be qualitatively described within these areas. Flooding conditions at the time of sampling will dictate sampling strategies to a degree. Efforts should be made to conduct soil descriptions when water levels are at their regular lowest point to allow for sampling throughout the turlough, taking into account all vegetation types and topographical variations. Plant-available forms of nutrients exhibit a greater degree of variation than more stable soil components and meaningful assessments of available nutrients would required a greater number of samples. Broad-scale nutrient assessments should focus on assessing more sTable nutrient components on dried soils rather than the various plant-available forms of N, P and K which are best conducted on moist soils within a few days of sampling. Information on total organic and total inorganic fractions would provide useful information on the potentially available and readily available soil nutrient status. On any given sampling occasion, large areas within a turlough may have potentially desiccated and saturated soils and analyses should aim to standardise among soil types and soil moisture contents. Soil moisture assessments and soil morphology descriptions should accompany any soil nutrient assessment at a given sampling point. In addition, management information such as levels of grazing, dung deposition and poaching should also be described at sampling locations to link soil nutrient status with different levels of management.

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APPENDIX A

Goodwillie (1992) vegetation maps available for Coole Lough (Inse Woods turlough), Garryland turlough, Caherglassaun turlough and Knockaunroe turlough.

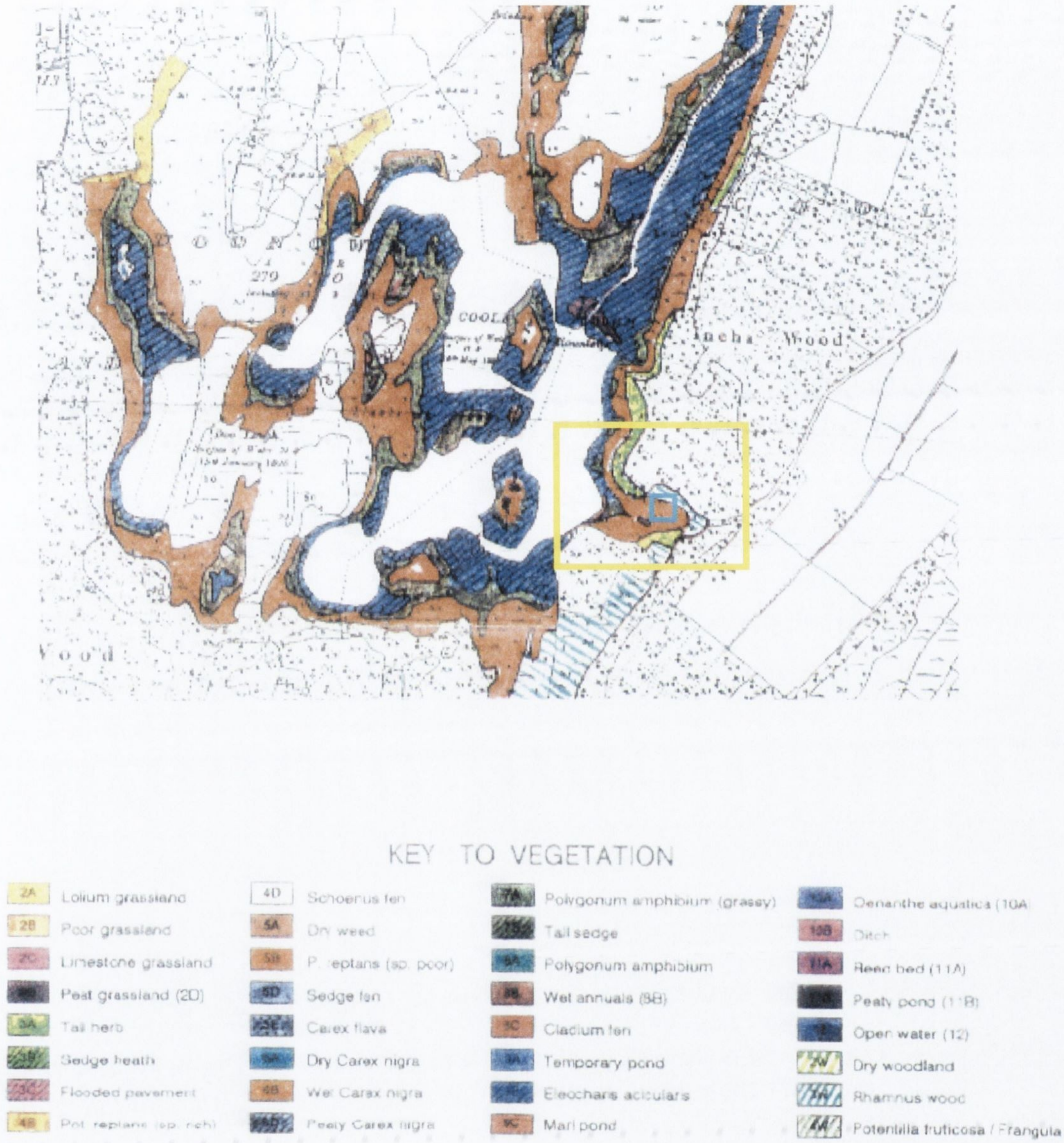

Figure 1: Goodwillie (1992) vegetation map for the Coole Lough area.

Temporal monitoring plots within 5B *Potentillla reptans* (spp. poor). (Chapter 4.)

Inse Woods Turlough

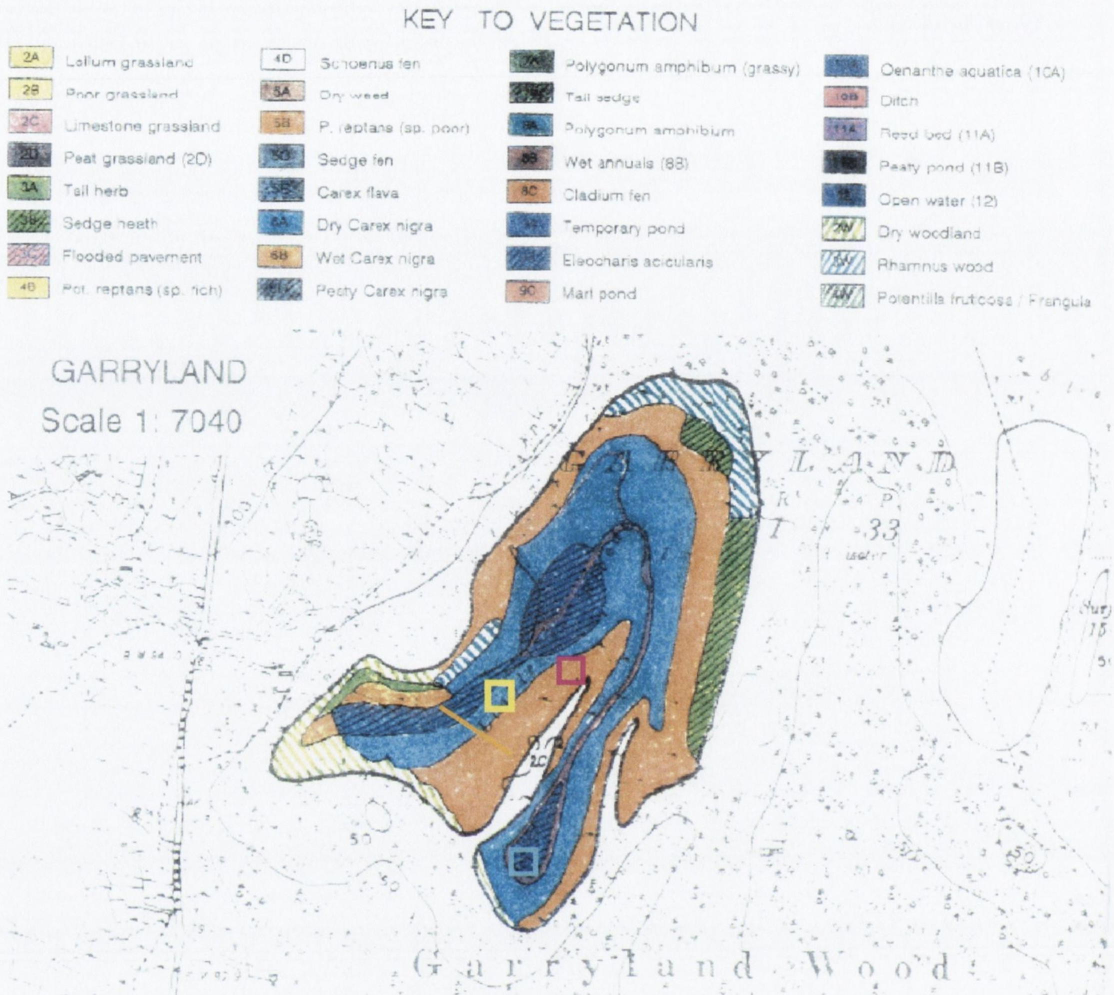

Figure 2: Goodwillie (1992) vegetation map for Garryland turlough.

Location of transect (Chapter 3.).

Location of temporal monitoring plots (Chapter 4.) within 6A Dry *Carex nigra*

Location of temporal monitoring plots (Chapter 4.) within 5B *Potentilla reptans* (spp. poor)

Location of temporal monitoring plots (Chapter 4.) within 9B *Eleocharis acicularis*

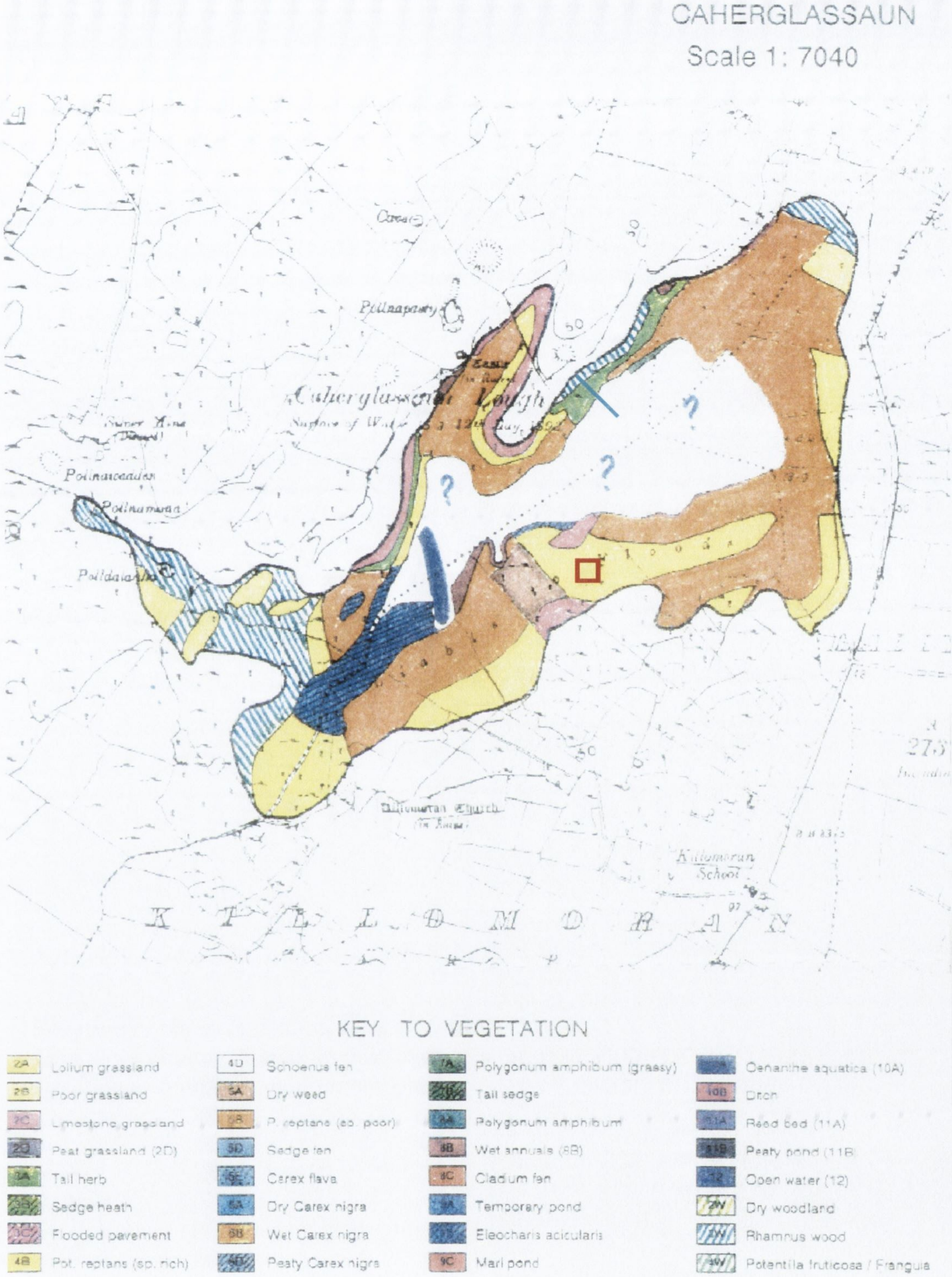

Figure 3: Goodwillie (1992) vegetation map for Caherglassaun turlough.
Location of transect (Chapter 3.).
Location of temporal monitoring plots (Chapter 4.) within 2A *Lolium* grassland.

Figure 4: Goodwillie (1992) vegetation map for Knockaunroe turlough.

- **Temporal monitoring plots within 3C. Flooded Pavement (Chapter 4.)**
- **Temporal monitoring plots within 9C. Marl Pond (Chapter 4.)**
- **Temporal monitoring plots within 4 W. Potentilla fruticosa scrub (Chaper 4.)**
- **Temporal monitoring plots within 7B. Tall Sedge (Chapter 4.)**
- **Temporal monitoring plots within 6B. Wet *Carex nigra* (Chapter 4.)**
- **Temporal monitoring plots within 4D. Schoenus Fen (Chapter 4.)**

APPENDIX B

Site Description and Soil Classification

Name of Recorder: Date: County/Turlough:

Transect Code: Releve No.: Size: Position on Transect:

Elevation of Quadrat: GR:

Basin Description

Swallow hole/ Drainage: Parent material:

Altitude:

Pit Description

Topography: S F D Aspect: Form: Cv S Cc

Gradient: 0-5, 6-10, 11-30, >30 GPS:

Stoniness: Rock Outcrops: R, VR, ER, RO

Samples	
Depth	
Colour	
Porosity	
Mottling	P / A
Abundance	
Size	
Contrast	
Boundaries	
Marl	P / A
Gleying	P / A

Nature of O (Peaty) Horizons	**Fibrous** **Semi-fibrous** **Amorphous**
Fauna	**P / A**
Marl	**P / A**

Weather:

Drainage/Water Level:

Surrounding Land Use and Topography:

APPENDIX C

Example of a date sheet used for vegetation descriptions

Turlough:		**Date:**		**Quadrat Number:**			
Grasses	**Score**	Cynosurus cristatus	**Score**	Trifolium repens			
Agrostis capillaris		Dactylorhiza incarnata		Viburnum opulus			
Agrostis stolonifera		Danthonia decumbens		Vicia cracca			
Alopecurus geniculatus		Eleocharis acicularis		Viola canina			
Anthoxanthum odoratum		Eleocharis multicaulis		Viola hybrid			
Briza media		Eleocharis palustris					
Crataegus monogyna		Elymus repens					
Deschampsia cespitosa		Filipendula ulmaria					
Festuca arundinacea		Frangula alnus					
Festuca pratensis		Fraxinus excelsoir					
Festucs rubra		Galium boreale					
Holcus lanatus		Galium palustre					
Lolium perenne		Galium verum					
Molinia caerulea		Geranium sanguineum					
Nardus stricta		Geum rivale					
Phleum pratense		Hydrocotyle vulgaris					
Poa pratensis		Hypericum maculatum					
Poa trivialis		Ilex aquifolium					
Sedges/Rushes/Aquatics		Lapsana communis					
Carex aquatilis		Leontodon autumnale					
Carex flacca		Leontodon taraxacoides		Notes on species			
Carex flava agg.		Linum catharticum					
Carex hirta		Litorella uniflora					
Carex hostiana		Lonicera periclymenum					
Carex lepidocarpa		Lotus corniculatus					
Carex nigra		Mentha aquatica					
Carex panicea		Mentha arvensis					
Carex pulicaris		Menyathes trifoliata					
Carex rostrata		Myosotis scorpioides					
Carex viridula		Myrica gale					
Carex vesicaria		Odontites verna					
Alisma plantago-aquatica		Ophioglossum vulgatum					
Apium inundatum		Parnassia palustris					
Baldiella ranunculoides		Phalaris arundinacea					
Campylium stellatum		Pimpinella saxifraga					
Chara spp.		Pinguicula vulgaris					
Cladium mariscus		Plantago lanceolata					
Drepanocladus revolvens		Plantago maritima					
Juncus articulatus		Polygonum hydropiper					
Juncus bulbosus		Polygonum persicaria					
Schoenus nigricans		Potentilla anserina					
Scirpus lacustris		Potentilla erecta					
Phragmites australis		Potentilla fruticosa					
Potamogeton coloratus		Potentilla reptans					
Potamogeton gramineus		Prunella vulgaris					
Potamogeton natans		Prunus spinosa					
Potamogeton polygonifolius		Pteridium aquilinum					
Equisetum fluviatile		Ranunculus acris					
Fontinalis antipyretica		Ranunculus flammula					
Glyceria fluitans		Ranunculus lingua					
Hippuris vulgaris		Ranunculus repens					
Iris pseudacorus		Rhamnus catartica					
Lemna trisulca		Rosa pimpinellifolia		**Domin Scale**			
Oenanthe aquatica		Rubus cesium		Single individual	plus		
Polygonum amphibium		Rubus fruticosa		1-2 individuals	1		
Rorippa amphiba		Rubus saxatile		< 1%	2		
Sparganium erectum		Rumex acetosa		1-4%	3		
Forbs/Woody		Rumex crispus		4-10%	4		
Achillea millefolium		Rumex obtusifolius		11-25%	5		
Achillea ptarmica		Salix repens		26-33%	6		
Anagallis tenella		Samolus valerandi		34-50%	7		
Angelica sylvestris		Scirpus lacustris		51-75%	8		
Asperula cynanchica		Senecio aquaticus		76-90%	9		
Bellis perennis		Senecio jacobaea		91-100%	10		
Calliergon giganteum		Sesleria albicans					
Caltha palustris		Stellaria media					
Campanula rotundifolia		Succisa pratensis					
Cardamine pratensis		Taraxacum officinale					
Centaurea nigra		Taraxacum Sect. palustris					
Cerastium fontanum		Teucrium scordium					
Cirsium arvense		Teucrium scorodonia					
Cirsium dissectum		Thymus serpyllum					

APPENDIX D

Determination of soil texture (Ball, 1986)

In the field or laboratory an estimate of soil texture can be made by gently rubbing a sample of the moist soil between thumb and forefinger-this is known as hand-texturing and the textural classes are listed below.

Texture	Texture characteristics
Sand	loose when dry, not at all sticky when wet
Loamy sand	has a small degree of cohesion and plasticity when wet
Sandy loam	sand fraction feel is obvious but the soil moulds readily when sufficiently moist, without stickiness
Loam	the soil moulds readily when moist but sticks slightly to fingers, though some grittiness from a sand fraction is still obvious
Silt loam	has moderate plasticity but little stickiness, with the smooth soapy feel of silt being conspicuous
Sandy clay loam	has sufficient clay to be quite sticky when moist, but the presence of a gritty sand fraction is still an obvious feature
Clay loam	again, sticky when moist, with just a slight sand fraction still detectable by its gritty contribution
Silty clay loam	less sticky than silty clay or clay loam, with elements of a slight sandy feel and a soapy feel due to the fraction
Sandy clay	plastic and sticky when moistened, and the sand fraction is obvious, but there is no modifying soft silty influence.
Clay	very sticky when moist, and very hard when dry
Silty clay	very low content of sand but the smooth silt contribution reduces the stickiness of the clay
Silt	dominated entirely by smooth soapy feel of silt faction
Organic	high organic content, not fitting into any of the above classes