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Four years of observations of carbon dioxide fluxes, water and energy budgets, and vegetation patterns in an Irish Atlantic blanket bog

Thesis presented by

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To a pint of Beamish or a pint of Murphys.

Or maybe both

Declaration

I declare that this thesis has not been previously submitted as an exercise for a degree at the National University of Ireland or any other university and I further declare that the work embodied in it is my own, or else noted.

Matteo Sottocornola

Abstract

Atlantic blanket bogs are peatlands that occur in maritime regions where precipitation is much greater than evapotranspiration. These ecosystems are rare but locally they are important for their role in carbon and water balance of regions and for their biodiversity value.

In this study we investigated CO_2, energy and water exchange in a pristine Atlantic blanket bog at Glencar, South-western Ireland, over a four-year period (2002-2006). A field survey of the vegetation patterns in relation to the environmental variation was also performed, which indicated that the distribution of the plant species was mainly explained by the depth of the water table. The bryophyte distribution was secondarily controlled by pH while the distribution of vascular plants was secondarily explained by the peat depth. The analyses of the vegetation gradients from the peatland centre to its borders indicate the existence of a pattern of variation along the natural margins but not along the artificial borders. This suggests that conservation policies should also include small blanket bog areas and that the natural borders should also be protected because they are likely to be rich in biodiversity and to have different vegetation to that of the bog centre. In addition, the vegetation survey identified the study site as typical of Atlantic blanket bogs in North-west Europe suggesting that the measured fluxes can be considered representative of this ecosystem in western Ireland.

The CO_2 uptake fluxes measured over the four years using an eddy covariance system ranged between –26.4 and –95.9 g C-CO_2 m^{-2}, showing a high interannual variability and values similar to boreal raised bogs, although both photosynthesis and respiration were lower. Over the four years, annual precipitation ranged from 2428 to 2742 mm yr^{-1} and evapotranspiration ranged from 357 to 406 mm yr^{-1}. The stream discharge measured over one hydrological year was 1852 mm. The water balance was dominated by stream discharge, while evapotranspiration was lower than in other peatland types, despite higher precipitation and water table. Evapotranspiration was limited by the low occurrence of both vascular plants and *Sphagnum* mosses, more than by the low vapour pressure deficit and cool summer air temperature.

A comparison between the four years suggests that the predicted climate change (increased rainfall in winter, decreased rainfall and increased air temperatures in summer) will probably increase winter evapotranspiration and cause an earlier start of the growing season. The expected decrease in summer precipitation may not radically affect the evapotranspiration pattern of the bog unless the frequency of summer rain events will diminish, causing the moss vegetation to become water-stressed. The ecosystem CO_2 uptake will probably decrease if summer rainfall will reduce (as predicted). Since the vegetation composition, the carbon, water and energy cycles are closely interconnected, modification of the vegetation or of any of these processes due to climate change will affect the other cycles and produce a vegetation change with complex feedbacks to the ecosystem functioning.

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1. Introduction

1.1 General introduction

Globally, northern peatlands are rare ecosystems, accounting for about 3 % of total land cover, but they contain between 270 and 450 Pg of carbon (C), which correspond to 20-30 % of the world's estimated soil C pool (Gorham, 1991; Turunen et al., 2002). The interest in C fluxes in peatlands has strongly increased in recent years since this large soil C reservoir is potentially available to the atmosphere if decomposition exceeds production due to climate change (Bubier et al., 1995).

The development of northern peatlands is closely related to regional climatic controls on precipitation, evaporation and temperature (Payette & Rochefort, 2001). The C exchange is thus strictly connected to the water and energy exchanges. The water budget in northern peatlands influences the ecosystem carbon sequestration (Shurpali et al., 1995; Lafleur et al., 2003) and the partitioning of the available energy (Brutsaert, 2005), other than affecting the soil chemistry (Laine et al., 1995) and the vegetation composition (Belyea & Clymo, 1998).

Climate change at northern latitudes is predicted to perturb the water and energy budgets (IPCC, 2001). As a result, climate change in northern peatlands is expected to affect both the vegetation composition (Weltzin et al., 2003) and the C cycle (Hilbert et al., 2000; Updegraff et al., 2001; Basiliko et al., 2005). A better understanding of the mechanisms linking these processes and of the interaction between them and the vegetation is therefore essential if we are to predict the impact of climate change on these fragile ecosystems (Belyea & Malmer, 2004).

Atlantic blanket bogs are rare peatland ecosystem, accounting for about 3 % of the global peatland area. Nevertheless regionally they can be abundant and important, not only for their uniqueness, but also for their biodiversity and their role in regional carbon and water balances. In the Republic of Ireland, they cover about 6 % of the land area and contain ca. 19 % of the nation soil carbon stock (Tomlinson, 2005). Although these ecosystems are worthy of conservation, only 21 % of Irish blanket bogs remain in relatively pristine conditions (Foss et al., 2001), which amplifies the need to enhance current conservation strategies (Douglas, 1998).

1.2 Aims and objectives

This study investigates the vegetation patterns of an Atlantic blanket bog, examining the link between the vegetation distribution and environmental factors, and the influence of the peatland borders on the vegetation. The study also analyses CO_2 fluxes, energy and water budgets and investigates the mechanisms governing and connecting these processes in Atlantic blanket bogs, exploring their correlation with the vegetation and their possible alteration due to the impact of climate change.

The study consists of four years of field measurements of eddy covariance CO_2 fluxes, water budget (consisting of precipitation, discharge and evapotranspiration) and energy exchange, in addition to a vegetation survey.

The study was divided in four projects, each of them with a specific aim:

1) Vegetation patterns of an Atlantic blanket bog in South-western Ireland (Chapter 4).
    a) Quantify the link between vegetation patterns and environmental variation.
    b) Investigate the effect of artificial and natural borders on the variation in vegetation composition.

2) An Atlantic blanket bog is a modest CO_2 sink (Chapter 5).
    a) Quantify the CO_2 source/sink status of an Atlantic blanket bog over two calendar years. This project has been extended to a four-year period (1st

October 2002 to 30th September 2006) and its results are shown in Appendix 1.

3) Water balance, evaporation and energy fluxes in an Atlantic blanket bog in South-western Ireland (Chapter 6).
    a) Describe the water and energy components in comparison with other peatland types.
    b) Investigate the evapotranspiration mechanisms.
    c) Analyse the interannual variations in the context of the predicted climate change for the South-west of Ireland.

4) A fourth project describing the comparison between eddy covariance and chamber techniques to estimate ecosystem CO_2 fluxes is presented in Appendix 3. Among the goals of this project was the investigation of how the patterned microform structure and shifting footprint affects the performance of the eddy covariance method (Chapter 3). This was a joint project with another Ph.D. student. The author was responsible for the eddy covariance data and footprint analyses.

1.3 Thesis layout

This thesis contains 8 chapters, a list of references and three appendices. Following the present Introduction, Chapter 2 is a literature review presenting the main topics about vegetation, CO_2, energy and water vapour fluxes in peatland ecosystems. The methodologies used to perform this work are presented in Chapter 3. Chapter 4 is dedicated to the vegetation survey, its analysis and results. Chapter 5 describes the CO_2 fluxes measured in the study site over the 2002-2003 period, while the results of the whole study period (1st October 2002-30th September 2006) are presented in Appendix 1. Chapter 6 analyses the energy and water budgets, with emphasis on evapotranspiration mechanisms, for the 4-year study period. Chapter 7 presents a general discussion of the thesis, while Chapter 8 lists the recommendations for future research.

2 Literature review

2.1 The peatland ecosystem

Peatlands are wetland ecosystems where the rate of production of organic matter exceeds its rate of decomposition (Bubier et al., 1995b). This imbalance is due to the inhibition of decomposition processes due to the high water table and consequent anoxic conditions, which results in the accumulation of partly decomposed organic material, as peat (Moore & Bellamy, 1974).

Northern peatlands are classified as bogs and fens. Ombrotrophic bogs receive water, nutrients and minerals only through precipitation and aerial deposition, while fens receive water input also from surrounding land (Gore, 1983). Bogs are divided in raised bogs and blanket bogs. Raised bogs are dome-shape peatlands, whose growth in elevation renders them independent of ground water influence (Gore, 1983). Blanket bogs are peatlands that form in response to a very humid climate (Gore, 1983). They are so called because they blanket the landscape (Tansley, 1965) on flat ground and on slopes with gradients up to 20-25° (Clymo, 1983; Tallis, 1998).

In the Republic of Ireland, peatlands are one of the most common landscapes, covering about 17 % of the national surface (Hammond, 1981; Eaton et al., submitted paper). The Irish climate is characterised by abundant and frequent rainfall throughout the year, with high relative humidity and mild temperatures (Rohan, 1986), so that a large fraction of Irish soils have a high tendency to retain water, becoming waterlogged and anaerobic, which is a prerequisite for peat development (Sheehy Skeffington & O'Connell, 1998).

2.2 The blanket bog ecosystem

2.2.1 Blanket bog distribution

Blanket bogs are a unique ecosystem, whose distribution is restricted to maritime conditions, with high precipitation (Hammond, 1981; Taylor, 1983), cool summers (Hammond, 1981) and mild winters (Doyle & Moore, 1978). These conditions occur only in particular regions, so that blanket bogs are common only in Newfoundland, Alaska, the Kamchatka peninsula, Japan, Chile and New Zealand (Lindsay, 1995), while in Europe they occur only in Norway, Great Britain and Ireland (Sheehy Skeffington & O'Connell, 1998). Blanket bogs are divided into Atlantic and Montane blanket bogs, depending on whether they are located at elevations lower or higher than 200 m asl (Foss et al., 2001). In Europe, Atlantic blanket bogs are common only in Scotland and Ireland, where they constitute the major global concentration of this unique ecosystem (Douglas, 1998).

2.2.2 Vegetation of blanket bogs

The surface of blanket bogs is often a mosaic of vegetation communities organised in undulating microforms: hummocks, lawns and hollows (Tallis, 1998). Hummocks are the highest microforms, rising from centimetres up to a metre over the general bog surface; hollows are the wettest microforms, completely submerged by standing water for most of the year, while lawns are microforms at an elevation in between hummocks and hollows.

Microforms differ in terms of pH (Doyle, 1982), water table (Belyea & Clymo, 1998) and plant composition (Doyle, 1990). The formation of a hummock-hollow pattern is triggered by a different rate of peat accumulation (Tallis, 1998). Tallis and Livett (1994) have discovered that the surface patterning in a blanket bog on the Pennines in England is a long-persistent feature; its hummock-hollow pattern is the result of different peat growth rates, which arose more than 2000 years ago within a rather featureless vegetation cover, probably in response to a climatic change towards drier conditions. Successive phases of dry and wet climatic periods, then contribute to shape the mire surface to produce its present hummock-hollow structure (Tallis, 1994).

The general vegetation of Atlantic blanket bogs in Ireland is dominated by graminoids, mainly *Molinia caerulea* (purple moor-grass) and *Schoenus nigricans* (black-top sedge), mostly occurring in lawns, while *Sphagnum* mosses (bog mosses) cover is low compared to raised bogs (Hammond, 1981; Doyle, 1990; Sheehy Skeffington & O'Connell, 1998). The hummock vegetation in Atlantic blanket bogs is characterized by a rich bryophyte community dominated by *Racomitrium lanuginosum* (wolly-hair moss) and some *Sphagnum* species, and by some vascular plants: *Calluna vulgaris* (common heather), *Erica tetralix* (cross-leaved heath), *Molinia caerulea* and *Schoenus nigricans* (Doyle, 1982). The hollow vegetation is characterized by a community dominated by some *Sphagnum* species and by vascular plants, such as *Menyanthes trifoliata* (buckbean) and sedges (Doyle, 1982; Doyle, 1990). The vegetation in lawns is poor in mosses, while the vascular flora is composed of the same plant occurring in the other microforms. Yet, vascular plants in lawns appear taller and denser than in hollows and the shrub growth is less vigorous than in hummocks (Doyle, 1982).

2.2.3 Environmental parameters in blanket bogs

The pH in Atlantic blanket bogs generally ranges between 4.2 and 4.7, which is higher than in raised bogs (Doyle, 1982; Doyle, 1990; Foss et al., 2001), because of the high ionic concentration in precipitation waters (Sparling, 1967). In Irish blanket bogs, sea origin ions (Cl^-, Mg^{2-} and Na^+) occur in higher amounts than in other ombrotrophic bogs around Europe (Doyle, 1982; Doyle, 1990). Nutrient (P and N) and Al concentrations are generally low compared to raised bogs (Doyle, 1982; Doyle, 1990).

The peat depth in blanket bogs averages 2 m (Tallis, 1998), ranging between 1 and 6-7 m (Hammond, 1981; Doyle, 1990), while the water table is constantly high, largely maintaining reducing conditions throughout the summer (Sparling, 1967).

The main factors explaining the vegetation pattern in northern peatlands are the water table depth, the chemical status and the distance from the peatland margins (Glaser et al., 1981; Malmer, 1986). The water table influences the water availability to plants (Lafleur et al., 2005) and the oxic-anoxic conditions (Laine et al., 1995), which determines the amount of nutrients available and the acidity of the peat soil. The distance to the peatland margins affects the vegetation distribution because the areas along the peatland borders are typically associated with deeper water table fluctuations, shallower peat depth and higher nutrient concentrations due to water inflow from the central part of the peatland. All these processes influence the soil chemistry and typically promote a greater plants growth than in the central parts of the peatland (Campbell & Rochefort, 2001).

2.2.4 Development of blanket bogs

The development and extensive spread of blanket bogs in Britain and Ireland occurred between 5100 and 3100 before present (BP) (Tallis, 1998), and only between 4500 and 4000 BP in western Ireland (O'Connell, 1990). It is now recognised that human activities had an important role in the expansion of blanket mires (O'Connell, 1990) due to forest removal by fire, grazing and trees cutting (Moore, 1993). The development of blanket bogs has since then, been influenced by climatic fluctuations, which provided alternating periods of more and less favourable conditions for peat growth (Tallis, 1998).

2.2.5 Conservation of blanket bogs

As Ireland is covered by a large proportion of global blanket bogs, it has a responsibility for their conservation (Douglas, 1998; Foss et al., 2001). Of the original 775,000 ha, only 21 % of blanket bogs are today relatively pristine in the Republic of Ireland (Foss et al., 2001), due to excessive grazing and trampling, peat extraction, afforestation and agricultural reclamation (Douglas, 1998). Therefore, there is a strong need for increased understanding of these ecosystems to enhance current conservation strategies (Foss et al., 2001). One of the unsolved issues on peatland conservation is the minimum size a site should be for successful conservation strategy (Tallis, 1998) (Chapter 4).

2.3 Carbon cycle in peatlands

The C budget of a peatland has three main components: CO_2 and CH_4 fluxes between the biosphere and the atmosphere, and dissolved organic carbon (DOC) losses in streams. The project on C cycling focuses on CO_2 fluxes, which are expected to be the largest part of the C cycle (Moore et al., 1998) (Chapter 5, Appendix 1).

The C cycle determines the development of the ecosystem as a whole and the formation of the hummock-hollow pattern, which is triggered by different rates of peat accumulation (Tallis, 1998). Different microforms show dissimilar CO_2 and CH_4 flux dynamics in peatland ecosystems (Alm et al., 1999; Waddington & Roulet, 2000), including Atlantic blanket bogs (Laine et al., 2007; Laine et al., in press). Even if the link between vegetation patterns and C dynamics has been identified, same microform types can vary largely in terms of C fluxes in different areas of the same peatland (Waddington & Roulet, 1996). This identifies the need to increase our understanding of the vegetation distribution patterns so as to improve our understanding of the carbon cycle in peatland ecosystems.

Carbon flux studies have been performed in peatlands with the chamber method (Whiting, 1994; Bubier et al., 1998; Waddington & Roulet, 2000) and eddy covariance techniques (Lafleur et al., 1997; Nieveen et al., 1998; Lafleur et al., 2001b; Lafleur et al., 2003) (Chapter 3). Most studies have been completed during the growing season only and over this time period, some peatlands have been net sources of CO_2 (Lafleur et al., 1997; Nieveen et al., 1998; Schreader et al., 1998), others have been sinks of CO_2 (Suyker et al., 1997; Vourlitis & Oechel, 1997; Aurela et al., 2001; Lafleur et al., 2001; Lafleur et al., 2001b), whereas other peatlands have been a sink or a source in different years (Shurpali et al., 1995;

Joiner et al., 1999; Griffis et al., 2000). More recent CO_2 studies using the EC techniques have been performed all-year round (Lafleur et al., 2003; Aurela et al., 2004).

Most of the studies on C dynamics in peatlands have been carried out in the boreal and sub-arctic regions and no long-term CO_2 measurements (to our knowledge) have been performed using the EC technique on a blanket bog.

The measured CO_2 fluxes represent the sum of CO_2 absorbed by plants during photosynthesis and the CO_2 released (respired) by plants as a product of their metabolic processes and by the soil as a product of soil decomposition (Begon et al., 1996). Photosynthesis and respiration are controlled by both abiotic and biotic factors. The main abiotic factors determining photosynthetic rates in peatlands are QPAR (photosynthetic active radiation), the light radiation used by plants to photosynthesise (Frolking et al., 1998), temperature and water availability (Laine et al., 2007). The biotic factors are mostly associated with the extent of the surface area of green vascular plant material present at a given time (Laine et al., 2007), which is determined by the leaf-out in spring and the senescence in the autumn. Evergreen vascular plants and bryophytes always carry their photosynthetic organs and can absorb CO_2 at any time of the year, if conditions are suitable for photosynthesis (Bubier et al., 1998). Respiration is also mostly controlled by temperature, water table and "greenness" of the vascular vegetation (Lloyd & Taylor, 1994; Laine et al., 2007).

2.4 Water budget in peatlands

The water budget in ombrotrophic bogs consists mainly of the input of water through precipitation minus the loss of water through stream discharge and evapotranspiration. Peatlands occur in different climatic conditions, so that the balance of these components varies largely. The precipitation in blanket bogs is very abundant and frequent and since these ecosystems can develop on rather steep slopes, the stream discharge is the dominant mechanism of water loss (Price, 1992). Stream discharge is typically small in raised bogs (Kellner & Halldin, 2002).

Evapotranspiration (ET) in wetlands is controlled by: the amount of available energy driving the process, by the ability of the atmosphere to hold and transport vapour and by the ability of the vegetation and soil to transport water through the atmosphere. Evapotranspiration differs in wetlands because these three factors differ (Roulet et al., 1997). Evapotranspiration in bogs appear to be lower than in other peatland types, most likely due to mechanisms related to vegetation, surface topography, water table, saturation vapour pressure deficit and energy, whose combination still remain unclear (Roulet et al., 1997; Lafleur et al., 2005). Evapotranspiration was observed to be lower in a blanket bog in Newfoundland compared with boreal raised bogs, due to smaller available energy and lower ability of the atmosphere to hold water (Price, 1991), i.e. low vapour pressure deficit (VPD).

Evapotranspiration from well watered vegetation surfaces defines the potential ET (PET), which is a widely used parameter because it can be more easily computed than actual ET (Lafleur et al., 2005). PET is normally estimated using the Penman-Monteith equation. Many studies in wetlands have therefore focused on the relationship between ET and PET, finding that PET is higher than the measured ET, despite the high availability of water in these ecosystems (e.g. Lafleur et al., 2005). In fact, ET does not appear to be strictly associated with water table height (Lafleur et al., 2005; Humphreys et al., 2006). Nevertheless actual ET is believed to experience physiological limitations (Humphreys et al., 2006).

More studies are therefore needed to resolve the apparent contradiction associated with actual ET, a crucial mechanism for peatland development and the C budget (Chapter 6).

2.5 Energy fluxes in peatlands

The energy budget defines how solar radiation is partitioned into sensible, latent and soil heat fluxes. The sensible heat flux is that part of net radiation (R_n) used for warming the air; the latent heat flux is that part of R_n used for water evaporation and plant transpiration; the soil heat flux is that part of solar energy used to heat the soil. For their impact on water availability, air and soil temperatures, these fluxes are crucial for any biotic and abiotic process in any ecosystems (Begon et al., 1996). Moreover the heat and water budgets significantly affect the C balance via interaction between biological and chemical processes (Belyea & Malmer, 2004). Therefore a better understanding of the surface energy and water exchange process are crucial to predict both future climate and C budgets (Moore et al., 1998; Letts et al., 2000) (Chapter 6).

2.6 Climate change in peatlands

Temperature is expected to globally rise a minimum of 2 °C in the next decades compared to pre-industrial time at equilibrium (IPCC, 2007), with northern latitudes predicted to experience the biggest increase (IPCC, 2001). Climate change scenarios for Ireland predict a raise of temperature between 1.25 and 1.5 °C, with precipitation expected to decrease by 10 % in June and increase between 10 and 25 % in December during the 2021-2060 period (McGrath et al., 2005), a trend that has been detected in the west of the country from the mid-1970s (Hoppe & Kiely, 1999; Kiely, 1999).

The warming in northern peatlands is expected to affect the hydrology (Roulet et al., 1992), vegetation zones and plant composition (Bubier et al., 1998; Verville et al., 1998), all factors influencing the C dynamics. Future change in C fluxes may be preferentially mediated by change in hydrology and vegetation composition rather than direct temperature effects on the biological processes (Moore & Knowles, 1989; Silvola et al., 1996; Nykänen et al., 1998; Verville et al., 1998).

The response of the C budget to climate change is difficult to predict due to the complexity of the soil-vegetation-hydrology relationships that determine the C cycle in peatlands. Moreover, the high heterogeneity of the microform structure of bogs can complicate the synthesis of the response of the ecosystem as a whole to climate change, due to their high spatial variation in water table, vegetation composition and chemical status (Strack & Waddington, 2007).

An increase in temperature will likely increase evapotranspiration, causing a drop in water table (Roulet et al., 1992). Higher temperatures and drier soils have been observed to stimulate an increase of CO_2 respiration relatively more than of photosynthetic activity, in the Alaskan arctic tundra, with consequent net C loss from the ecosystem (Oechel et al., 1993; Oechel et al., 2000). Nevertheless, a drop of water table and vegetation succession in wet peatland areas could increase the net uptake of C, due to a decrease in methane emissions (Strack et al., 2006). Moreover an earlier start of the growing season due to warmer spring temperatures could offset the expected increase in respiration due to higher soil temperatures (Aurela et al., 2004; Basiliko et al., 2005).

Continuous and long term measurements of C and energy budgets in peatlands are therefore needed to increase our understanding of the mechanisms governing these ecosystems and ultimately to be able to predict the effects that a change in the present environmental conditions will produce.

3 Materials and Methods

3.1 Site description

3.1.1 Location

This study was conducted in an Atlantic blanket bog located near Glencar, County Kerry, in Southwest Ireland (Latitude: 51° 55' N, Longitude: 9° 55' W) (Figure 3.1). The peatland study area covers approximately 450 ha and lies on sandstone bedrock. The site is located in a valley at an elevation between 145 and 170 m above sea level (Figure 3.2 and 6.1).

Figure 3.1: location of the Glencar Atlantic blanket bog.

The bog is composed of a large central pristine part, surrounded by disturbed peatland areas. The southern and western parts of the bog are affected by occasional sheep grazing. The eastern part of the peatland (~30 ha) is under restoration. This area was drained and afforested about 30 years ago. The restoration effort started in the autumn of 2003: drainage ditches were blocked, trees were cut and left on site. The blanket bog is cut by a road, northern of which there are signs of past manual peat harvesting. The present study was confined to the blanket bog pristine central part (~ 220 ha), enclosed on the north by the road, on the east by the restoration area, on the south by the area of occasional grazing and on the west by one of the two streams that drains the bog complex (see Figure 3.2).

3.1.2 Climate

The 30-year average temperature at the Met Eirann synoptic weather station at Valentia (ca. 30 km West of Glencar) for the warmest month of the year (August) was 14.8 ºC, and for the coldest (February) was 6.6 ºC. The 30-year average annual precipitation was 1430 mm yr^{-1}. In the same period, the average number of rainy and wet days was 239 and 187, respectively. The years 2002 to 2006 in Valentia have been on average 0.9 ºC warmer and ca. 8 % wetter than 30-year average

(http://www.meteireann.ie/climate/valentia.asp).

3.2 Methods of the vegetation survey

3.2.1 Vegetation survey

A vegetation survey can be carried out following either the classification or the ordination methods (Kershaw & Looney, 1985). The classification approach aims to find the differences between vegetation communities and to delimit groups of different vegetation patterns. The ordination approach aims to highlight the continuity in the vegetation variation and to relate this variation to the variation of the environmental conditions. In this study the aims were to explore the links between the vegetation patterns and the changing environmental variables and to investigate the gradients of variation in vegetation communities and in environmental conditions, rather than to classify the vegetation. The ordination approach was therefore followed (Chapter 4).

The vegetation survey was performed over an area of about 70 ha, in the pristine part of the bog. This area is enclosed on the north by the road, on the west by the eastern stream, on the east by the peatland restoration sector and on the south by an area where occasional sheep grazing occurs (Figure 3.2).

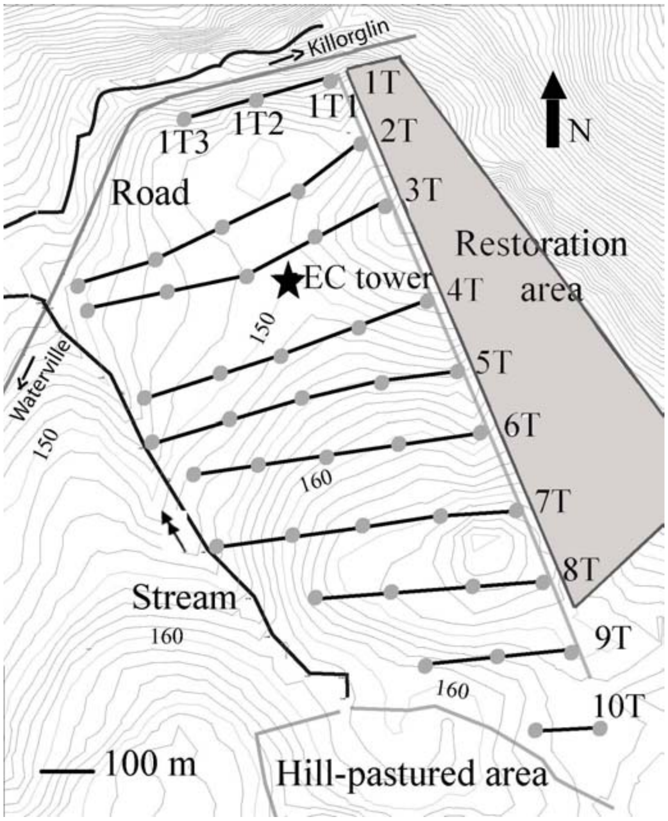

Figure 3.2: part of the study site where the vegetation was surveyed. The grid design followed in the survey was set up along a fence located in the eastern part of the bog. The grid consisted of 10 transects (marked with a T in the figure). Each grid point along the transect was defined by a progressive number following the transect number, as indicated for transect 1 (1T). EC tower is the location of the eddy covariance tower.

The vegetation survey was carried out between the 10^{th} and the 31^{st} of August 2005 using a grid design with a 150 m interval (Figure 3.2). The grid was set up along the eastern fence bordering the restoration area, where ten transects had their origin points. The grid was composed of 42 grid points. At each grid point, 8 sample plots were radially placed at a random distance between 1 and 3 m. In total 336 sample plots were surveyed by estimating the projection cover of each plant species (%) inside 0.3 × 0.3 m quadrats.

The grid design was chosen because it allows a wide and objective sampling of the vegetation, the latter being a requisite for the application of ordination methods (Kershaw & Looney, 1985). The use of small sample plots facilitates the visual estimates of single plant species, especially mosses, but it can deceive the actual vegetation occurrence in a given area. Eight sample plots were therefore surveyed at each grid point to capture, at each point, the full and accurate variation of the plant occurrence.

Together with the plant cover, some environmental parameters were also measured. These were variables that were observed to be important in explaining the vegetation distribution in other peatland types, namely water table, chemical status and distance from the peatland margin (Glaser et al., 1981; Malmer, 1986). pH, electric conductivity, water colour and concentrations of Na^+, Ca^{2+}, Cl^-, SO_4^{2-} and total organic nitrogen (TON) were analysed from ground water samples. Peat depth was also measured, since it was expected to be shallower close to the peatland edges, and possibly influencing the plant distribution (Chapter 4).

3.2.2 Statistical analyses

Statistical analyses were performed on both the plant species and environmental parameters (Figure 4.1 and Table 4.2). With the first analysis the aim was to determine if the percentage cover of bryophytes and vascular plants significantly differed in the microform types (Figure 4.1). An analysis of variance (ANOVA) was therefore performed. One of the most important assumptions of an ANOVA is the homogeneity of the variance (Zar, 1996), which can be checked with the Levene's test. Since this requirement was not respected by the plant species data (Levene's test significance < 0.05), a nonparametric ANOVA was used. A nonparametric ANOVA does not require an estimation of the population variance or mean and do not make any assumption about the parameters of distributions (Zar, 1996). A Kruskal-Wallis test was used, followed by a Mann Whitney test. The Kruskal-Wallis test is a nonparametric test that indicates the existence of significant difference between the averages of the considered dataset, while the

Mann Whitney test verifies which of the means differ (Zar, 1996). The Mann Whitney test is one of the most powerful among the nonparametric tests but, since it is not based on the actual data but on their transformation in ranks, is less reliable than the one-way ANOVAs (Zar, 1996).

The same approach was followed for the analyses of the environmental parameter measured in the different microforms (Table 4.2). The Levene's test was significant for pH and high water table. A Kruskal-Wallis followed by a Mann-Whitney test was therefore applied to these variables, as done for the plant species. The Levene's test for all other environmental parameters was not significant, indicating that the requirement for homogeneity of the variance was respected in these cases. A one-way ANOVA was therefore applied to the remaining environmental variables followed by a Tukey test, if the ANOVA indicated significant difference in the microform types. The Tukey test is a robust multiple comparison test, which identifies the measurement means that statistically differ (Zar, 1996). Low water table and SO_4^{2-} concentration showed a significant difference between the microforms (Table 4.2).

3.2.3 Ordination analyses

The link between vegetation patterns and environmental variation and the distribution of the vegetation communities and plant species was investigated using ordination analyses (Chapter 4). Ordination techniques are gradient analysis methods widely used in vegetation pattern description (e.g. Glaser et al., 1990; Bubier et al., 1995; Hájková et al., 2006). They order objects numerically and graphically on each of several axes so that similar objects are near and dissimilar objects are far from each other. The goal of the ordination technique is to find axes of the greatest variability in the continuum of community compositions (Lepš & Šmilauer, 2003). Ordination analyses are divided into indirect gradient analyses (as Principal Component Analysis (PCA) and Detrended Correspondence Analysis (DCA)) and direct gradient analyses (as Canonical Correspondence Analysis, CCA). Indirect gradient analyses are not based on environmental variables; they aim to compute the ordination axes as "latent" variables that represent the best predictors for the values of all the species and community data. The axes of direct gradient analyses are instead computed as linear combinations of the environmental variables (Ter Braak, 1986). The goal of direct gradient analysis is to find the variability in species composition that can be explained by the measured environmental variables (Lepš & Šmilauer, 2003). By using the constrained approach the main part of the biological variability explained by the measured environmental variables is considered, but the main part of the variability not related to the measured environmental variability can be missed (Lepš & Šmilauer, 2003).

Since we believe to have measured the main environmental parameters influencing the vegetation pattern, a direct constrained technique, CCA, was used in the data analysis. We applied CCA to relate vegetation patterns and plant species to environmental parameters and to explore the variation of both vegetation and environmental variables along the artificial and natural bog borders, to investigate the influence of the peatland margins on the vegetation composition (Chapter 4).

3.2.3 Vegetation survey data analyses

The CCA was computed through the weighted averaging method and with a biplot scaling procedure. The weighted averaging method was chosen rather than a linear method, because it well represents unimodal curves, which characterise the species distribution responses to environmental variables when a wide range of the species distribution is covered by the sample dataset (Lepš & Šmilauer, 2003). This was the case in Glencar. We applied the biplot scaling procedure because it provides diagrams that can be interpreted in a more quantitative way, in comparison to the diagram resulting from a Hill's scaling approach (Lepš & Šmilauer, 2003). The significance of the CCA axes was tested with Monte Carlo permutation tests. Together with the axes significance, the eigenvalue of the axes, the percentage of the plant distribution explained by the axes, and the inter set correlation of environmental variables with the axes was also reported. The eigenvalue represents a measure of the explanatory power of the single axis while the inter set correlation represents the correspondence between environmental parameters and the CCA axes (Lepš & Šmilauer, 2003). To perform the analyses we used the software CANOCO version 4.5 for Windows (Ter Braak & Šmilauer, 2002) (Chapter 4).

Canonical correspondence analysis was applied to species and sample datasets separately. In the analysis focusing on the species, only percentage cover of plants occurring in at least five of the 336 surveyed plots were included, to reduce the influence of low occurring species. The distances from the peatland borders were used as covariables to exclude the location of the plant species in the analysis and to explore the influence of chemical and physical parameters on the plant distribution in the blanket bog. The environmental measurements considered in the CCA therefore were the high and low water tables, the peat depth and the chemical parameters: pH, corrected conductivity, NH_4^+, TON, Na^+, Ca^{2+}, Cl^-, SO_4^{2-} and colour. We performed separate analyses for bryophytes and vascular plants, with the purpose of discovering the vegetation-environmental gradients for the two different plant groups (Chapter 4).

The significant responses of the most common species to the main environmental gradients were further investigated using a generalized additive model (GAM) procedure. The GAM is a type of regression model, an extension of Generalized Linear Models (GLMs), where the effect of a particular predictor on the response variable is not expressed using a linear combination of the predictor values, as in the GLMs, but by a smooth semi-parametric term, based on a smoothing model (Ter Braak & Šmilauer, 2002). Therefore, the GAMs have a less rigid form than GLMs and determine the unknown shape of the response curve (Ter Braak & Šmilauer, 2002). The performance of the individual model is verified using an Akaike Information Criterion (AIC), a procedure that measures the parsimony of the model (Ter Braak & Šmilauer, 2002) (Chapter 4).

Canonical correspondence analysis was also applied to the sample plot dataset. Since we were interested in investigating the role of the artificial and natural borders on the vegetation community distribution, the CCA was performed using only the distances from the peatland borders as explanatory variables. Water chemistry, peat depth and water table data were not used in the CCA but were plotted as supplementary variables, so that the different peatland locations could be characterised environmentally. In the same way, plant species were displayed in a separate graph to investigate the relationship between the species and the peatland sectors (Chapter 4).

3.3 Micrometeorological theory

3.3.1 Atmospheric boundary layer

The Atmospheric Boundary Layer (ABL) is the lower part of the troposphere, the part that interacts with the biosphere. The ABL is directly influenced by the presence of the earth's surface, and responds to surface forcings with a timescale of about an hour or less. These forcings include frictional drag, evapotranspiration, heat transfer and terrain induced flow modification (Stull, 1988). The depth of the ABL is variable and ranges between few tens of metres (when it is stably stratified, typically at night time) to several km (when it is unstable, typically at day time).

The Atmospheric Boundary Layer can be divided in two regions (Kaimal & Finnigan, 1994):

- An inner part, called the Surface Layer (SL), which is approximately the lower 10 % of the ABL. In the SL the shearing stress and the vertical fluxes of conserved quantities can be considered constant in the vertical direction, while concentrations vary approximately logarithmically with height (Daebberdt et al., 1993). In this layer the wind flow is not dependent on the earth's rotation and the wind structure is primarily determined by surface friction and the vertical gradient of temperature (Kaimal & Finnigan, 1994).

- An outer region, which extends above the SL up to 500-1000 m. In this layer the shearing stress is variable and the wind structure is influenced by surface friction, temperature gradient and the earth rotation.

3.3.2 Atmospheric motions

Atmospheric motions are distinguished by temporal and spatial scales. Temporal scales can range between months and a fraction of second, while spatial scales can range between thousand of kilometres to a few millimetres. On this basis, atmospheric motions are divided in three categories: macro-scale, characterised by temporal and spatial scales of the order of a week and more than 1000 km, respectively; meso-scale with dimensions ranging from hundreds of km to hundreds of metres and periods of days; micro-scale atmospheric motions, with spatial scales ranging from 1 km to 1 mm and temporal scales ranging between few minutes to a fraction of a second. Micrometeorology is related to meteorological processes on the micro-scale category (Stull, 1988).

3.3.3 Turbulent kinetic equation

Airflow, or wind, can be divided in three components: mean wind, turbulence and waves. Each part can exist in the boundary layer, where transport of quantities (such as moisture, heat, momentum or trace gases) is dominated in the horizontal direction by the mean wind (advection), and in the vertical direction by turbulence. Waves can be generated locally by mean-wind shears and by mean flow over obstacles (Stull, 1988).

Two mechanisms are responsible for the production of turbulence in the boundary layer: wind shear and buoyancy.

Wind shear is generated by the friction of two layers of air moving at a different velocity or by the drag exerted by rough surfaces on the main wind. Since the transfer of momentum is always downwards, wind shear always creates turbulence.

Buoyancy is a measure of the change of air density with height and is the result of the combination of two forces: weight and Archimedes force. When an air parcel has lower density than surrounding air (due to higher temperature or humidity), it accelerates upwards creating turbulence in a process called positive buoyancy. When an air parcel has a higher density than the surrounding air (due to lower temperature or humidity), it accelerates downwards, suppressing turbulence in a process called negative buoyancy.

3.3.4 Potential temperature and atmospheric conditions

Potential temperature is the temperature that an air parcel would have if brought adiabatically to the pressure at the 1000 mb level (Kaimal & Finnigan, 1994). The vertical gradient of temperature, also called the temperature profile, defines buoyancy and plays a fundamental role in describing the motion of air parcels, through the definition of atmospheric conditions: neutral, unstable and stable atmospheric conditions (Stull, 1988).

- In neutral conditions the vertical gradient of the potential temperature is zero, thus there is no variation of potential temperature with height. Parcels of air displaced up and down adiabatically maintain exactly the same density as the surrounding air, experiencing no net buoyancy effects. Wind speed increases according to the logarithmic wind profile. Neutral stability conditions are often transitory.

- Unstable conditions generally occur during the day when the soil surface is heated by solar radiation and the layer of air just above it is then heated by the ground through irradiance, inducing a thermal mixing. In these conditions, the potential temperature decreases with height; the air temperature thus decreases vertically faster than the adiabatic lapse rate. Parcels of air displaced up will be warmer than surrounding air and continue to rise, generating a condition of instability or mixed convection.

- Stable conditions generally occur during the night when air immediately above the soil cools due to proximity of the cold soil surface. In these conditions, the potential temperature increases with height because air close to the surface is cooler than above; the air temperature thus decreases vertically slower than the adiabatic lapse rate. Parcels of air displaced up will be cooler than surroundings and will drop again, suppressing turbulence created by wind shear; in this case, buoyancy suppresses turbulence.

The commonly used measure of atmospheric stability in the surface layer is the Monin-Obukhov length. The Monin-Obukhov similarity theory is based on expressing vertical gradients and turbulent statistics of variables in the Surface Layer as functions of only –z/L, where z is the height over the ground and L is the Obukhov length. L is defined as the ratio of the turbulent energy produced and consumed by buoyancy to the turbulent energy generated by wind shear (Daebberdt et al., 1993).

3.3.5 Turbulent flows

Turbulent flows in the atmospheric boundary layer can be thought as the superposition of eddies, thus coherent patterns of velocity, vorticity and pressure, spread over a wide range of eddy sizes (Kaimal & Finnigan, 1994). These eddies interact continuously with the mean flow, from which they derive their energy, and with each other. The eddies are responsible for most of the transport in turbulence and arise through instabilities in the background flow. Eddies are unstable entities that loose energy through the interaction with other eddies and the ground, breaking down into smaller eddies till they are so small that viscosity can convert their kinetic energy into heat (Kaimal & Finnigan, 1994). Turbulent motions are irregular, quasi random motions where some organised behaviour can be recognised. It is possible to express eddy intensity versus eddy frequency, using spectral analysis. It is generally observed that two major peaks of intensity occur, separately by an energy gap in eddies intensity over the range of the eddy frequency: the first peak corresponds to a few days range (macro-scale frequency) and is linked to general atmospheric phenomena, such as weather fronts. The second peak corresponds to a turbulence scale peak (micro-scale frequency). Almost no energy is observed in the meso-scale eddy frequency: this supports the approach of the eddy covariance (EC) technique, since it allows the separation of the turbulent scale frequencies (Stull, 1988) (see 3.4.1).

3.4 The Eddy Covariance methodology

3.4.1 Eddy Covariance technique

A flux is the transfer of a quantity per unit area per unit time. An eddy flux is a transfer of a quantity by the turbulent motion of air. Eddy covariance is a micrometeorological technique that measures the turbulent flux across the vegetation canopy-atmosphere layer to determine the net difference of material moving across this interface (Lenschow, 1995; Baldocchi, 2003). Two fast response instruments are necessary for EC measurements: a 3-D sonic anemometer and an infrared gas analyser, both operating at high frequency (generally at 10 Hz), to cover the full range of the turbulent motion.

In the Glencar Atlantic blanket bog, we used an open-path infrared gas analyser (Chapter 5 and 6, Appendix 1 and 2). Compared to close-path sensors, the open-path gas analyser has easier computational requirements and causes less aerodynamic disturbance, due to its open structure (Baldocchi, 2003). The main disadvantage of an open-path sensor is its poor performance during rainy conditions. The flux data were logged on a CR23X data logger (Campbell Scientific, UK). Since this data logger does not have a very powerful memory, the 10 Hz data were averaged online over a 30-minute period based on a running-mean approach (Aubinet et al., 2000) and 10 Hz data were then discarded, reducing the possibility for further analysis of 10 Hz measured data.

The EC approach is based on the existence of the wind spectral gap; this allows the statistical separation of the mean term of the wind velocity or trace gas concentration (varying over several-hour periods) from their turbulent parts (varying over periods of tens of seconds), using the Reynold's rule of averaging (Stull, 1988):

$$\xi = \overline{\xi} + \xi' \qquad (3.1)$$

where ξ is any instantaneous turbulent variable, $\overline{\xi}$ is its mean term and ξ' is its fluctuating component.

Considering CO_2 as an example of a trace gas, the flux across the canopy-atmosphere layer is defined as the statistical covariance of the wind speed in the vertical direction and the CO_2 concentration:

$$F_c = \overline{w\rho_c} \tag{3.2}$$

Following the Reynold's rule of averaging, the previous equation can be decomposed as:

$$F_c = \overline{w}\overline{\rho_c} + \overline{w'\rho_c'} \tag{3.3}$$

This equation indicates that the total vertical flux of any scalar is the sum of a mean vertical flux $\overline{w}\overline{\rho_c}$ and an eddy flux $\overline{w'\rho_c'}$ (Moncrieff et al., 1997). One assumption normally made is that over a suitable interval of time there is no mass movement of air in the vertical, i.e. $\overline{w} = 0$ and therefore

$$F_c = \overline{w'\rho_c'} \tag{3.4}$$

This approximation is not completely exact since $\overline{w}$ is not zero but to small to be detected by instruments and is therefore computed on the basis of temperature and humidity density, using a correction algorithm, the so called Webb correction (Moncrieff et al., 1997). The trace gas density, ρ_c' can indeed vary due to the variation of the air density caused by sensible and/or latent heat fluxes. The effect of these fluxes on air density is considered in the Webb correction.

Latent and sensible fluxes can be estimated with the EC technique in a similar way as the CO_2 fluxes. The latent heat flux (LE) is computed as:

$$LE \cong L_v \overline{w'\rho_v'} \tag{3.5}$$

where L_v is the latent heat of vaporization (kJ kg^{-1}), w' is the vertical wind velocity fluctuations (m s^{-1}) and ρ_v' is the water vapour density fluctuation (g m^{-3}).

The sensible heat flux (H) is computed as:

$$H \cong \rho_a c_p \overline{w'T'} \tag{3.6}$$

where ρ_a is the moist air density (kg m^{-3}), c_p is the specific heat capacity of moist air (J kg^{-1} °C^{-1}) and T' the temperature fluctuations (°C).

For the present study, the CO_2 (Chapter 5, Appendix 1), the latent and the sensible heat fluxes (Chapter 6) were measured and computed using equation 3.4, 3.5 and 3.6 respectively. The micrometeorological convention (used in this work) treats fluxes from the atmosphere as negative and fluxes from the ecosystem as positive. The measured CO_2 flux was considered to correspond to the net ecosystem exchange (NEE), because the stored flux in the canopy was considered negligible in this treeless ecosystem for most of the day (Lafleur et al., 2003).

3.4.2 Advantages and limitation of the Eddy Covariance technique

The EC system is today a widely used technique for the measurements of gas fluxes between the atmosphere and natural ecosystems (Baldocchi, 2003), because of its many advantages. The EC system allows whole ecosystem gas exchange measurements 1) through direct measurements, 2) over large sampling areas, 3) across a range of time scales, 4) without disturbing the studied ecosystem (Baldocchi et al., 1988; Baldocchi, 2003). The main weaknesses of the EC techniques lie in the underestimation of the ecosystem night fluxes, due generally to low turbulence conditions (Baldocchi, 2003), and in the uncertainties about the source location (footprint) of the materials flux (Sogachev & Lloyd, 2004) (see paragraph 3.4.3).

In addition, the assumptions of stationarity and homogeneity should be fulfilled so that the fluxes measured by the EC system are representative of the biosphere-atmosphere material exchange.

- Stationarity means that statistical properties of the flow do not vary in time. This condition can not be realized in its strict sense because of the long-term variation in the atmosphere. But dividing time series of atmospheric processes in sequences of steady-state periods, we are allowed to use time averages that represent the processes. Sampling duration should be long enough to account for the spectrum of eddies that contribute to the transfer processes (Baldocchi, 2003), but not too long to be affected by diurnal changes of the measured trace gas (Lenschow, 1995). Time periods of 15 minutes to 1 hour have been used in the past. The Carboeurope periods are standardized at 30 minutes (Voronovich & Kiely, 2007), which is what we used.

- Homogeneity means that the flow is horizontally homogeneous and therefore its statistical properties are independent of their horizontal position but they vary only with height and time (Kaimal & Finnigan, 1994). In these conditions, time series from a probe moving through the flow can be used to spatially estimate a varying field of turbulence (Lenschow, 1995). To satisfy this condition, the system has to be mounted above a flat terrain.
- The atmospheric turbulence has to be well developed so that the turbulent transport is much bigger than molecular diffusion (Vourlitis & Oechel, 1997).
- The underlying vegetation extends upwind from the system for an extended distance (Baldocchi, 2003) (see below).

In the Glencar study site, the EC system was installed in an area, which is relatively flat, that is surrounded by at least 250-300 m of uninterrupted bog vegetation in any direction. An averaging time of 30 minutes was chosen, as generally applied in EC studies (Chapter 5 and 6).

One of the biggest problems using the EC technique is the measurements of the night time fluxes (Baldocchi, 2003). Typically at night the stable atmospheric conditions tend to depress turbulence, causing a reduction of atmospheric mixing. In these conditions, the trace gas can accumulate close to the ground, not reaching the sensor height, causing night time gas flux underestimations (Baldocchi, 2003). To cope with this problem, the turbulent mixing of the atmosphere is generally verified through the observation of the extent of the friction velocity; gas fluxes measured during periods with unsatisfactory low friction velocity conditions are excluded (Aubinet et al., 2000).

Night time CO_2 flux measurements in Glencar did not show a clear response to friction velocity nor a clear threshold of friction velocity for unsatisfactory turbulent mixing. Nevertheless, a considerable part (46 %) of CO_2 fluxes measured in dry night periods had negative value, indicating an ecologically unreasonable CO_2 uptake during the night. All night time negative CO_2 fluxes were rejected (Chapter 5, Appendix 1).

When calculating gas fluxes with the EC method over a long period, the errors associated with the 30-min flux affect the total uncertainty of the long-term trace gas fluxes in different ways. Following Moncrieff et al. (1996), the errors can be divided in three categories:

1) a random error originates in a 30-min flux value mainly from the statistical uncertainties connected with the EC method; it decreases when extending the data set, being therefore typically low in an annual balance.
2) Possible systematic errors, as an insufficient coverage of the high frequencies contributing to the turbulent fluxes. This type of error has a more severe effect on the annual balance, since it does not diminish in a longer dataset.
3) Selective systematic bias affects unevenly the upward or downward fluxes and has therefore a potential for greater errors, such as the underestimation of night fluxes (Goulden et al., 1996).

An error analysis on the EC system in Glencar was performed following the approach of Aurela et al. (2002) and Moncrieff et al. (1996). The systematic and random components of error were estimated (Chapter 5). The energy balance closure was used to estimate the systematic error, which was between 30 and 35 % (see Figure 6.17). The random component of the error, which was much lower, was estimated based on the measured and modelled values of NEE, as:

$$Error_{random} = \sqrt{\sum \frac{(NEE_{meas} - NEE_{\mathrm{mod}})^2}{(n-1)*n}} \tag{3.7}$$

where NEE_{meas} is the measured NEE and NEE_{mod} is the modelled based NEE.

3.4.3 Footprint analysis

The upwind spatial distribution of the corresponding surface emission (or deposition) flux was called footprint by Schuepp et al. (1990). The footprint is defined as the contribution, per unit emission, of each element of the upwind surface area source to the measured vertical scalar flux measured at a height z (Schuepp et al., 1990). Three different approaches to footprint estimation are used:

- Eulerian analytical models. These are relatively simple models, easier to implement, that usually assume a Gaussian distribution of turbulence characteristics along the direction of the main flow (prevailing wind direction) and that generally prescribe a spatially homogeneous source located at a fixed height (Sogachev & Lloyd, 2004). Eulerian models determine an area of influence on measurements by physically-based criteria instead of empirical criteria (Vesala et al., 2004) Their weakness lies in the exclusion of any consideration of turbulent diffusion in the streamwise direction (Sogachev & Lloyd, 2004). These models use parameters designed largely for use over homogeneous surfaces. When used over heterogeneous surfaces, an averaging of those parameters (e.g. roughness length or Obukhov length) remains at best a first-order approximation (Vesala et al., 2004). Nevertheless Göckede, et al. (2004) showed that analytical models are robust and provide realistic even under real, non-ideal conditions. Examples of these models were developed by Horst and Weil (1992; 1994) and Schuepp et al. (1990).
- Lagrangian-stochastic dispersion models. These models provide a direct estimate of the transport pathways. Compared to the Eulerian models, the Lagrangian models are more flexible and can account for 3D turbulent diffusion, non-Gaussian and inhomogeneous turbulence characteristics (Sogachev & Lloyd, 2004). The Lagrangian-stochastic approach is based on the

assumption that the evolution of position and velocity of a fluid element is described by a Markov process (Hsieh et al., 2000), thus a random process whose future probabilities are determined by its most recent values. The weakness of the Lagrangian-stochastic approach is the need for relatively detailed knowledge of turbulent flow characteristics (Sogachev & Lloyd, 2004). These footprint models are generally much less used than Eulerian models because of their high computational requirements. Examples of these models were developed by Hsieh et al. (1997), Flesch (1996) and Leclerc and Thurtell (1990).

- Large eddy simulation (LES) approach. These models can simulate the turbulence statistics and the scalar concentration field under any given conditions (Sogachev & Lloyd, 2004). The LES models are free of a pre-described turbulence field and can also cope with horizontal inhomogeneity, but are computationally expensive and limited to relatively simple flow conditions by a number of grid points in the flow simulation. This approach is a trade-off between the level of complexity of the model and computational expense using a closure model of suitable order (Vesala et al., 2004).

For our footprint analysis we used an eulerian analytical model developed by Hsieh et al. (2000) (Chapter 5 and 6, Appendix 1 and 2). This model is based on a combination of Lagrangian stochastic dispersion model results and dimensional analysis. The main advantage of this model is its ability to analytically relate atmospheric stability, measurement height and surface roughness length to flux and footprint. The model by Hsieh et al. (2000) estimates the location of the peak and of the length of the positive skew distribution curve that defines the footprint. A cut-off at 67 % of the footprint length was used to filter fluxes originating from outside the pristine part of the bog (see 3.4.4, Chapter 6, Appendix 1). Furthermore the definition of the 67 % of the footprint length was used as a cut-off point for the upscale of chamber measurements to the EC footprint with the aim of comparing CO_2 fluxes measured with the EC and chamber techniques (Appendix 3).

3.4.4 Data processing and filtering

After we obtained the raw fluxes, a series of post-field data processing has to be performed and filters have to be established to ensure the quality of the measured gas fluxes (Aubinet et al., 2000). In Glencar the following procedure and filters were implemented over time, partially used in Chapter 5 and fully employed for the figures in Appendix 1:

- Online processing:

  10 Hz data was logged online and underwent the following online filters before being computer as 30-minute average fluxes. These filters excluded fluxes if:

  1) the gas analyser or 3-D sonic anemometer data were lower or higher predetermined values (CO_2 concentrations < 5 or > 35 mmol m^{-3}; water vapour concentration < 50 or > 1050 mmol m^{-3}; temperature < -10 or > 40 ºC); or if
  2) the air temperature measured with the 3-D sonic anemometer differed of more than 5 ºC with air temperature measured with an air temperature probe (T_{air}) (see chapter 5).
  3) the water vapour concentration measured with the gas analyser differed of more than 200 mmol m^{-3} than that calculated from the relative humidity and T_{air} measured with an air temperature-relative humidity probe (see chapter 5).

- Post processing:

  Good 10 Hz flux data were then averaged over the 30-minute and were subject to correction and further filters before being accepted as "good half-hour fluxes". The correction included:

  1) a double rotation on the raw EC flux data, so that the mean horizontal wind speed was rotated into the mean wind direction and the mean vertical wind velocity was set to zero, by correcting the fluxes for the averaged 30-minute angle between the horizontal and vertical axes (Lee et al., 2004).

2) The CO_2 and LE fluxes were corrected for variation in air density (Webb et al., 1980), while H was corrected for moist air (Shotanus et al., 1983).

The post processing filters excluded fluxes, if:

1) the 30 minutes fluxes were the result of the average of less than 95 % of good 10 Hz data (thus if less than 10 Hz data passed the online filters for that half hour); or if
2) the estimate of the vertical angle gave unrealistic outputs (typically in low wind speed conditions); or if
3) less than 67 % of the flux footprint length (Hsieh et al., 2000) was estimated to have originated from outside the pristine part of the bog; or if
4) the fluxes were measured during rainy periods or up to one hour after rain, because of the poor performance of the open-path gas analyser in wet conditions.

Moreover, CO_2 fluxes were excluded for realistic threshold values (Table 3.2). The filter used were rather conservative and resulted in good CO_2 fluxes for the daytime as being 56 % of total daytime fluxes in 2002/03, 67 % in 2003/04, 51 % in 2004/05 and 63 % in 2005/06. For the night, good CO_2 fluxes occurred 22 % in 2002/03, 26 % in 2003/04, 23 % in 2004/05 and 29 % in 2005/06.

LE were further rejected during the post processing, if:

a) the product between net radiation (R_n) and H gave a negative output; or if
b) LE was lower than –30 and higher than 280 W m^{-2};
c) winter LE were filtered for predetermined realistic threshold values for each month (Table 3.1).

Table 3.1. Defined winter LE limits for the four years.

LE	October	November	Dec-15th Jan	15th Jan-Feb	March
upper limit	< 150 W m^{-2}	< 80 W m^{-2}	< 70 W m^{-2}	< 100 W m^{-2}	< 160 W m^{-2}

Table 3.2 Filters, fitting equations, fitting variables and R^2 for CO_2 fluxes at day and night for the four years.

2002/03	μmol m^{-2} s^{-1}	**October**	**Nov-Dec**	**Jan-Feb**	**Mar-Apr**	**May**	**June**	**July-Aug**	**September**
Day	F_c threshold	$-4< F_c <1$	$-2.5< F_c <1$	$-2< F_c <1$	$-2.6< F_c <1.5$	$-5< F_c <1.5$	$-6< F_c <1.5$	$-8< F_c <2$	$-6< F_c <2$
Day	Fitting equation	Rectangular hyperbola	Rectangular hyperbola	Ratio const/qua	Ratio qua/lin	Ratio const/qua	Rectangular hyperbola	Rectangular hyperbola	Rectangular hyperbola
Day	Fitting var.; R^2	QPAR; $R^2=0.44$	QPAR; $R^2=0.20$	T_{air}; $R^2=0.14$	QPAR; $R^2=0.12$	T_{air}; $R^2=0.14$	QPAR; $R^2=0.53$	QPAR; $R^2=0.43$	QPAR; $R^2=0.39$
Night	F_c threshold	$0< F_c <1.5$	$0< F_c <1.5$	$0< F_c <1$	$0< F_c <1.5$	$0< F_c <2$	$0< F_c <2$	$0< F_c <5$	$0< F_c <3.5$
2003/04	μmol m^{-2} s^{-1}	**October**	**Nov-Dec**	**Jan-Feb**	**March**	**April**	**May-June**	**July-Aug**	**September**
Day	F_c threshold	$-4< F_c <1.5$	$-2.5< F_c <1$	$-2.5< F_c <1$	$-2.5< F_c <1.5$	$-3< F_c <1.5$	$-7< F_c <1.5$	$-7< F_c <2$	$-6.5< F_c <1.5$
Day	Fitting equation	Ratio qua/lin	Rectangular hyperbola	Ratio qua/lin	Ratio qua/lin	Ratio const/qua	Rectangular hyperbola	Rectangular hyperbola	Ratio lin/lin
Day	Fitting var.; R^2	QPAR; $R^2=0.16$	QPAR; $R^2=0.12$	QPAR; $R^2=0.31$	QPAR; $R^2=0.19$	T_{air}; $R^2=0.13$	QPAR; $R^2=0.23$	QPAR; $R^2=0.44$	QPAR; $R^2=0.26$
Night	F_c threshold	$0< F_c <3$	$0< F_c <2.5$	$0< F_c <1.5$	$0< F_c <2$	$0< F_c <2$	$0< F_c <4$	$0< F_c <6$	$0< F_c <4$
2004/05	μmol m^{-2} s^{-1}	**October**	**Nov-Dec**	**Jan-Feb**	**March**	**April**	**May-June**	**July-Aug**	**September**
Day	F_c threshold	$-5< F_c <1.5$	$-3< F_c <1$	$-2< F_c <1$	$-2.5< F_c <2$	$-3.5< F_c <2$	$-8< F_c <2.5$	$-9< F_c <2.5$	$-6.5< F_c <1.5$
Day	Fitting equation	Rectangular hyperbola	Rectangular hyperbola	Ratio const/qua	Ratio qua/lin	Ratio const/qua	Ratio cub/lin	Rectangular hyperbola	Rectangular hyperbola
Day	Fitting var.; R^2	QPAR; $R^2=0.32$	QPAR; $R^2=0.24$	T_{air}; $R^2=0.22$	QPAR; $R^2=0.13$	QPAR; $R^2=0.09$	QPAR; $R^2=0.20$	QPAR; $R^2=0.46$	QPAR; $R^2=0.45$
Night	F_c threshold	$0< F_c <3$	$0< F_c <2$	$0< F_c <1.5$	$0< F_c <1.5$	$0< F_c <2$	$0< F_c <4$	$0< F_c <5$	$0< F_c <3.5$
2005/06	μmol m^{-2} s^{-1}	**October**	**Nov-Dec**	**Jan-Feb**	**March**	**April**	**May-June**	**July-Aug**	**September**
Day	F_c threshold	$-3< F_c <1.5$	$-2.5< F_c <1$	$-2< F_c <1$	$-2.7< F_c <1$	$-3< F_c <2.5$	$-5< F_c <2$	$-8< F_c <2$	$-7< F_c <1.5$
Day	Fitting equation	Rectangular hyperbola	Rectangular hyperbola	Ratio qua/lin	Ratio lin/qua	Ratio qua/lin	Rectangular hyperbola	Rectangular hyperbola	Rectangular hyperbola
Day	Fitting var.; R^2	QPAR; $R^2=0.44$	QPAR; $R^2=0.14$	QPAR; $R^2=0.14$	T_{air}; $R^2=0.21$	QPAR; $R^2=0.22$	QPAR; $R^2=0.23$	QPAR; $R^2=0.48$	QPAR; $R^2=0.37$
Night	F_c threshold	$0< F_c <3.5$	$0< F_c<2.35$	$0< F_c <1.5$	$0< F_c <1.5$	$0< F_c <1.5$	$0< F_c <3$	$0< F_c <3.5$	$0< F_c <3.5$
2002-2006		**Night** Fitting equation: Exponential Q_{10} equation. Fitting variable: T_{soil} @ 20cm; $R^2= 0.21$							

3.4.5 Gapfilling

In the estimation of seasonal or annual balances of trace gas exchange, the missing fluxes need to be replaced by modelled values to obtain a continuous dataset. The missing CO_2 gas fluxes in Glencar were replaced by nonlinear regression equations relating the gas flux and either QPAR or temperature. Separate gapfilling equations were established for day and night time data. Day and night were defined setting 10 W m^{-2} of short-wave incoming radiation as the threshold. In this way, 45 % of all 4-year data were considered day time data, and 55 % night time data. Day time data were then divided in monthly or bimonthly datasets (Table 3.2) and relations between CO_2 fluxes and either QPAR or air temperature were established. The division of the period and the choice of the predictor environmental variable depended on the best fit found. Summer months were gapfilled using a rectangular hyperbola type of equation, which ecologically defines the NEE response to light conditions (Frolking et al., 1998):

$$NEE_{day} = \frac{\alpha * QPAR * P_{\max}}{\alpha * QPAR + P_{\max}} + R \tag{3.8}$$

where α is the initial slope of the rectangular hyperbola (also called apparent quantum yield), P_{max} is the maximum ecosystem gross photosynthesis and R is the y axis intercept, which defines the dark respiration value.

In other seasons, the NEE response at high light intensity is influenced by the associated higher temperatures, which cause a decrease in NEE due to an increase in ecosystem respiration. In these conditions, the rectangular hyperbola equation performs poorly. A similar family of equations, the polynomial equations in one variable of different orders, was used instead (Table 3.1). This same type of equation was used to relate T_{air} to NEE in those periods where NEE was better explained by the variation of temperature than of light.

Night time data were gapifilled using a van't Hoff empirical exponential equation (Lloyd & Taylor, 1994), relating the half hour CO_2 flux with 20 cm deep soil temperature (T_{soil}) for the full four-year period:

$$NEE_{night} = a * b^{(T_{soil} - 10)/10} \tag{3.9}$$

where a (µmol m^{-2} s^{-1}) and b (ºC) are coefficients. Although the van't Hoff equation is empirical and has no ecological basis, it has been extensively used in ecology (e.g. Lafleur et al., 2001b):

These regression equations were defined using the Curve Fitting Function of MATLAB 7.0.1 software (MathWorks Inc., USA) for monthly or bimonthly periods (see Table 3.1). Only polynomial equations were applied in Chapter 5, while the more ecologically meaningful rectangular hyperbola equations were used to produce the CO_2 fluxes included in Appendix 1.

Missing LE fluxes were replaced using for each year a linear regression equation relating the 30-minute good daytime measured LE and a modeled daytime 30-minute LE. This was based on the potential evapotranspiration (LE_{PET}), created using the Curve Fitting Tool of MATLAB 7.0.1 (MathWorks Inc., USA). The Penman-Monteith equation, with surface resistance (r_s) set to zero, was used as an estimate of LE_{PET}:

$$LE_{PET} = \frac{\Delta * (R_n - G) + \rho_a * c_p * (\frac{VPD}{r_a})}{\Delta + \gamma} \tag{3.10}$$

where Δ is the slope of the relationship between saturation vapour pressure and temperature, VPD is the vapour pressure deficit (kPa), r_a is the atmospheric resistance (s m^{-1}) and γ is the psychrometric constant (kPa / °C).

Missing H fluxes were replaced with solving the energy balance equation for H:

$$H = (R_n - G) - LE \tag{3.11}$$

Gaps occurred also in meteorological data, due to electricity outages, replacement or unsatisfactory performance of instruments. Short meteorological gaps (up to 4 hours) were replaced by the interpolation between the last measured data before and the first measured data after the gap, except for radiation. With gaps longer than 4 hours, the meteorological data were replaced by the average of the previous and following 7 days for the missing half-hour. The latter method was applied to radiation data as well, unless any radiation measurement was present. In this case, missing shortwave incoming radiation data were modelled based on a linear relationship with QPAR values (R^2=0.99), while missing R_n data were replaced by a linear relationship with QPAR incoming radiation (R^2=0.94).

Vegetation patterns of an Atlantic blanket bog in South-western Ireland

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4.1 Summary

1 A vegetation survey was carried out in an Atlantic blanket bog in Southwest Ireland to study the vegetation patterns in relation to environmental variation and to quantify the effect of artificial and natural borders on compositional variation. Canonical correspondence analysis was applied for data analysis.

2 The results indicate that, in terms of both vegetation and water chemistry, the study site can be categorized as typical of Atlantic blanket bogs in the maritime regions of North-western Europe. A large part of the bog is dominated by lawn vegetation; elsewhere the surface pattern is a mosaic of hollows, lawns and hummocks.

3 The distribution of plant species was mainly explained by the depth of the water table. The distribution of bryophytes was secondarily explained by the pH of the bog water, while the distribution of vascular plants was explained by peat depth.

4 The vegetation distribution exhibited little variation between the central pristine sector of the peatland and its disturbed edges (hill-grazing and restoration areas) but a substantial variation was observed between the area along a stream and the areas close to the other peatland borders or centre. Similarly the internal variation within each sector (centre, hill-grazing edge and restoration area edge) was small, but substantial variation was observed within the area located along the stream. This area was associated with deeper water table, shallower peat depth, higher DOC and NH_4^+ concentrations, and lower Cl^- concentrations in the bog water. Our results suggest the existence of strong centre-margin gradients in Atlantic blanket bogs and indicate that human or animal disturbance may be restricted to the damaged area.

5 Our results indicate that small Atlantic blanket bogs are worthy of conservation and that such measures should include sectors close to the natural peatland borders, where a distinct vegetation, rich in biodiversity, is likely to occur. Climate change is expected to cause a drop in summer water table and pH. Since bryophyte distribution is controlled by both these factors, and since they have a narrower niche than vascular plants, it is likely that climate change will affect bryophyte more than vascular plant distribution.

4.2 Introduction

Blanket bogs are ombrotrophic peatlands whose development is mostly independent of basin or topographical features where water can collect. They are so called because they blanket the landscape (Tansley, 1965) on slopes with gradients up to 20-25° (Tallis, 1998). Globally, blanket bogs are rare, accounting for ca. 3 % of the world peatland area (Foss et al., 2001). These ecosystems are important not only for their uniqueness but also for their biodiversity and role in regional carbon and water balances. The distribution of blanket bogs is restricted to temperate maritime regions, since their development requires cool summers and January mean temperatures > 4 °C (Doyle & Moore, 1978). Precipitation is high (> 1250 mm yr^{-1}), with more than 225 rainy days (Hammond, 1981; Taylor, 1983) or 160 wet days (i.e. > 1 mm day^{-1}) per year (Tallis, 1998). Furthermore, precipitation exceeds evapotranspiration by at least 200 mm over the growing season period (April-September) (Tallis, 1998).

Blanket bogs are classified as Atlantic (lowland) or Montane, depending on whether they are located at elevations lower or higher than 200 m asl (Foss et al., 2001). In Europe, Atlantic blanket bogs are common only in Scotland and Ireland, where they constitute the major global concentration of this ecosystem (Douglas, 1998). In the Republic of Ireland, they cover about 6 % of the land area and contain ca. 19 % of the nation soil carbon stock (Tomlinson, 2005). Although these ecosystems are worthy of conservation, only 21 % of blanket bogs remain in relatively pristine conditions (Foss et al., 2001), due to peat extraction, drainage and forest plantation. Therefore there is a strong need for increased understanding of these ecosystems to enhance current conservation strategies (Douglas, 1998).

The vegetation of Atlantic blanket bogs in Ireland is typically dominated by graminoids, mainly *Molinia caerulea* and *Schoenus nigricans*, while the bryophyte cover is low compared to raised bogs (Hammond, 1981; Doyle, 1990; Sheehy Skeffington & O'Connell, 1998). The high presence of minerotrophic plants (e.g. *Schoenus nigricans*) has been explained by the high concentration of mineral ions of maritime origin in the peat waters (Sheehy Skeffington & O'Connell, 1998). Together with the permanently high water table, the high ionic concentration is responsible for the high pH (Pearsall & Lind, 1941; Gorham, 1953; Sparling, 1967) compared to raised bogs (4.2-4.7 and 3.5- 4.2, respectively, reviewed by Doyle (1982; 1990)).

The surface of blanket bogs is often a mosaic of vegetation communities organised in undulating microforms: hummocks, lawns and hollows (Tallis, 1998). These microforms are supported by differences in water table (Belyea & Clymo, 1998), which controls the vegetation composition (Doyle, 1990) and pH (Doyle, 1982). The formation of a hummock-hollow pattern is triggered by different rates of peat accumulation (Tallis, 1998), since different microforms exhibit dissimilar CO_2 and CH_4 flux dynamics (Laine et al., 2007; Laine et al., in press). The resulting carbon balance is therefore strongly connected with both vegetation and environmental factors. Environmental factors are expected to be perturbed as a consequence of climate change. Therefore a better understanding of their interaction with ecosystem functioning and vegetation patterns is essential if we are to predict the impact of climate change on these fragile ecosystems.

In northern peatlands, the vegetation pattern is affected by three main factors: depth of the water table, chemical status and distance from the peatland margin (Glaser et al., 1981; Malmer, 1986). The relative importance of these gradients depends on the regional characteristics of geology, hydrology and topography (Bubier et al., 1995). Although the link between vegetation composition and environmental factors is well studied in raised bogs (e.g. Belyea & Clymo, 1998), in blanket bogs less is known. Studies on blanket bogs are few in number and have mostly focused on stratigraphy (Conway, 1954; Chapman, 1964; Moore, 1977; Tallis, 1994; Tallis & Livett, 1994) or on pure vegetation description (Doyle & Moore, 1978; Doyle, 1982; Doyle, 1990). Although the most direct approach to study the relationship between vegetation and environmental parameters is the ordination technique (e.g. Glaser et al., 1990), to our knowledge no such study has been performed in Atlantic blanket bogs. Moreover, the natural large scale internal variation within blanket bogs has not been investigated, although in peatland ecosystems it has been found to form an important ecological gradient, associated with variation in plant composition (Wheeler & Proctor, 2000; Økland et al., 2001).

In this study we aimed to quantify (1) the link between vegetation patterns and environmental variation, and (2) the effect of artificial and natural borders on variation in vegetation composition in an Atlantic blanket bog.

4.3 Material and methods

4.3.1 Study site

The study was conducted in a 220 ha Atlantic blanket bog located at ca. 150 m above sea level near Glencar, County Kerry, in Southwest Ireland (Latitude: 51° 55' N, Longitude: 9° 55' W). In the study site, the average temperature for the warmest month of the year (August) during the 2003-2006 period was 15.3 ºC, and for the coldest (February) was 6.1 ºC. The average annual precipitation over the same period was 2570 mm yr^{-1}, while the average number of rainy and wet days was 270 and 209, respectively (see Sottocornola & Kiely, 2005). At the nearby Met Eireann synoptic weather station at Valentia (30 km west of the study site), the air temperature for the period 2003-2006 was about 0.9 ºC warmer and the rainfall was 8 % higher than its 30 years average (http://www.meteireann.ie/climate/valentia.asp).

The vegetation survey was carried out over an area of about 70 ha, in the pristine part of the bog. The study area is enclosed on the northern side by a road and on the west by a bog stream. On the east the site is bordered by a peatland area, which had previously been afforested and is under restoration since 2003. The southern limit of the study site is marked by a fence, beyond which occasional sheep grazing occurs. This area stretches for about 200 m on the blanket bog before meeting a slope covered by few small patches of fertilized grassland on the side of a 300 m high ridge. Hereafter this area is referred to as the “hill-grazing area”.

4.3.2 Vegetation survey

The vegetation survey was carried out between the 10th and the 31st of August 2005 using a grid design. The grid interval was 150 m and it was set along the fence bordering the restoration area to the east. All the grid points on the eastern edge were placed at 5 m distance from this fence. On the northern side the grid ran roughly parallel to the road, approximately 30 m distant from it. On the southern end, the grid approached the fence delimiting the edge of the hill-grazing area; the distance from the closest grid point to the fence was 27 m. To extensively survey the area of the peatland close to the stream on the west side, the frequency of the grid between the two final points before the stream was reduced to 125 m along two transects. The distance from the closest point to the stream was 3 m. The survey included 42 grid points. At each grid point, 8 sample plots were radially placed at a random distance from 1 to 3 m. In total 336 sample plots were surveyed by estimating the projection cover of each plant species (%) inside 0.3 × 0.3 m quadrats. The plant cover was assessed to the nearest 1 % for plant species with coverage less than 25 % and to the nearest 5 % for plant species with coverage greater than 25 %. For very low plant occurrence, 0.01, 0.1 and 0.5 % covers were also assigned.

4.3.3 Environmental measurements

At each sample plot, the peat depth was measured with a 2 m long iron probe and the microform type was identified. Four different types of microform were identified based on their relative elevation: hummocks, high lawns, low lawns and hollows (see Laine et al., 2006). A bamboo stick covered with PVC insulating tape was inserted into the peat in the middle of each sample plot to assess the highest and lowest water table. The PVC tape becomes discoloured in reduced conditions and therefore gives an estimate of the fluctuation in water table (Belyea, 1999). The bamboo sticks were inserted in August 2005 and collected on the 8th December 2005. Unexpectedly, one of the brands of PVC tape did not react. Moreover, while the mark of the lower water table was clear, the highest marks appeared vague. Only the estimates of the lowest water table from a part of the sample plots were therefore used in the data analysis.

Sampling wells were inserted into the peat to collect water samples for chemical analysis. Each well consisted of a 4.5 cm diameter PVC pipe pierced with 4 mm diameter holes on opposite sides every 2.5 cm, closed at the top and bottom with polyethylene caps. A hole was first dug into the peat using a sharp edge tube of the same diameter as the sampling wells. Sampling wells were then carefully pushed into the ground avoiding peat compression. At each grid point, one sampling well per each microform type, out of the eight sample plots, was installed. A maximum of four wells were installed at one grid point if all four microform types occurred. In total, 86 sampling wells were installed: 20 in hummocks, 42 in high lawns, 15 in low lawns and 9 in hollows. To estimate the missing high water table marks, the water table was measured inside all the 86 sampling wells on the 3rd of May 2006, during a period of very high precipitation (ca. 70 mm of rain in the previous three days).

4.3.4 Chemical analysis

Water samples for chemical analysis were collected in 150 ml polyethylene bottles using an electric water pump on the 13th, 14th and 20th of December 2005. The first water obtained from the sampling wells was used to rinse the bottles and then discarded. Aeration of the samples was avoided by filling the bottles completely. The bottles were then stored in a cool box and brought to the water chemistry laboratory the same evening, stored in a refrigerator at 4 ºC and analysed within 24 hours of collection. Conductivity and pH were measured in the field, directly inside the sampling wells, after the collection of the water samples. Conductivity was measured using a WTW LF 330 conductivity meter (Geotech Environmental Equipment, Inc., USA). Following this, pH was measured using a WTW pH 320 (Geotech Environmental Equipment, Inc., USA). A two-point calibration with 4.00 and 7.00 pH standards was used. Temperature corrections for conductivity and pH were automatically performed to a reference temperature of 25 °C; conductivity was also corrected for proton concentrations using an equivalent conductivity of 349.6 $\mu S\ cm^{-1}$ per meq $H^+\ l^{-1}$ (25 °C) (Miller et al., 1988). Due to the occurrence of very low water table, it was not possible to measure the conductivity in two of the 86 sampling wells. To perform full statistical analysis these two measurements were replaced by the mean of the conductivity of the other samples from the same microform type.

The water samples were analysed by the Aquatic Services Unit of the Environmental Research Institute at University College Cork (Ireland) using a Lachat QuikChem IC+FIA 8000 (Lachat Instruments, Colorado, USA). Na^+, Ca^{2+}, Cl^-, SO_4^{2-} were measured using a QuikChem Ion Chromatographer. NH_4^+ and total organic nitrogen (TON) were analysed using a QuikChem Flow Injection Analyser. Water colour, which is a proxy for dissolved organic carbon (DOC) concentration, was measured at 455 nm using a spectrophotometer (UV-160A Shimadzu, Kyoto, Japan).

4.3.5 Data analyses

Plant species and sample plots data were analysed by canonical correspondence analysis (CCA) through the weighted averaging method, using the software CANOCO version 4.5 for Windows (Ter Braak & Šmilauer, 2002).

Partial canonical correspondence analysis was first used to find the variability in the species composition that was best explained by the measured environmental variables (Lepš & Šmilauer, 2003). For this analysis, the effect of the sample plot location in the peatland was removed, by using the distances from the peatland borders as covariables. A biplot scaling procedure was used. The significance of the environmental variables and of the resulting CCA axes, which were linear combinations of the selected environmental variables, was tested with Monte Carlo permutation tests. Since we expected the environmental controls for different plant groups to vary, we performed separate analyses for bryophytes and vascular plants. Only the species, which occurred in at least five of the 336 surveyed plots, were included in these analyses.

The significant responses of the most common species to the main environmental gradients were further investigated using a generalized additive model (GAM) procedure with a Poisson distribution curve. The GAM diagrams were used to support the interpretation of the ordination analyses on the species distribution.

To investigate the effect of artificial and natural borders on the vegetation, we performed a CCA using only the distances from the peatland borders as explanatory variables. To identify the environmental variation related to the different peatland sectors, the peat depth, water table and water chemistry variables were included as supplementary variables into the CCA. Water chemistry values and missing water table measurements were extended to the same microform types in each grid point. The plant species were then displayed in a separate diagram to investigate the relationship between the species and the peatland sectors. The CCA, with biplot scaling, was applied to the whole sample plot dataset and used all the plant species observed. The significance of the CCA axes was tested with Monte Carlo permutation tests.

4.4 Results

4.4.1 General features of the plant communities

During the vegetation survey, 32 vascular plants and 39 bryophytes species were identified; of the latter, 16 species were liverworts, 11 were *Sphagnum* species and 12 were Bryopsida (Table 1). On average the bryophytes covered 25 % of the peatland area: *Racomitrium lanuginosum*, *Sphagnum rubellum*, *Pleurozia purpurea*, *S. papillosum* and *S. tenellum* were the most abundant and, together with *Mylia anomala* and *Kurzia pauciflora*, the most frequent species observed in the sample plots. The average vascular plants cover was about 30 %. *Molinia caerulea*, *Calluna vulgaris*, *Erica tetralix* and *Narthecium ossifragum* were the most abundant species and, together with *Eriophorum angustifolium*, were also the most frequent vascular plants. The plant occurrence followed a clear trend, with percentage cover of both bryophytes and vascular species significantly decreasing along the water table gradient, from hummocks to hollows. The only exceptions were the bryophytes, which were more abundant in hollows than in low lawns (Figure 4.1).

Table 4.1 (next page). Mean percentage cover (and frequency) of the plant species in the blanket bog (All) and in the four different identified microforms. r = percentage cover < 0.5; + = percentage cover ≥ 0.5 % and < 1 %. **Cephalozia* species were not distinguished on the field but just in the lab; it was therefore not possible to assign the cover.

Plants nomenclature follows, for Hepaticeae: Smith, A. J. E. (1990) *The liverworts of Britain and Ireland*. Cambridge University Press, Cambridge. For Sphagnopsida (except *S. rubellum* Wils.): Daniels, R. E. & A. Eddy (1990) *Handbook of European Sphagna*. 2nd edn, HMSO, London. For Bryopsida: Smith, A. J. E. (1978) *The moss flora of Britain & Ireland*. Cambridge University Press, Cambridge. For vascular plants: Stace, C. (1997) *New Flora of the British Isles*. 2nd edn. Cambridge University Press, Cambridge.

	Code	All	(336)	HU	(31)	HL	(259)	LL	(29)	HO	(10)
Hepaticae											
Kurzia pauciflora (Dicks.) Grolle	*Kur pau*	r	(250)	r	(20)	r	(203)	r	(19)	r	(1)
Calypogeia sphagnicola (H. Arn. & J. Perss.) Warnst. & Loeske	*Cal sph*	r	(19)	.		r	(19)	.		.	
Cephalozia cfr. bicuspidata (L.) Dum.* *Cephalozia cfr. connivens* (Dicks.) Lindb.*	*Cep.zia*	r	(31)	r	(2)	r	(27)	r	(2)	.	
Nowellia curvifolia (Dicks.) Mitt.	*Now cur*	r	(5)	+	(2)	r	(3)	.		.	
Cladopodiella fluitans (Nees) Buch	*Clad flu*	r	(34)	r	(2)	r	(22)	r	(6)	r	(2)
Cephaloziella sp. (Spruce) Schiffn.	*Cep.lla*	r	(187)	r	(18)	r	(153)	r	(8)	r	(3)
Odontoschisma sphagni (Dicks.) Dum.	*Odo sph*	r	(204)	r	(19)	r	(173)	r	(6)	r	(1)
Mylia anomala (Hook.) S.F. Gray	*Myl ano*	r	(302)	1	(31)	r	(247)	r	(16)	r	(1)
Diplophyllum albicans (L.) Dum.	*Dip alb*	r	(52)	r	(3)	r	(46)	r	(1)	.	
Scapania nemorea (L.) Grolle	*Sca nem*	r	(1)	.		r	(1)	.		.	
Scapania gracilis Lindb.	*Sca gra*	r	(2)	.		r	(2)	.		.	
Lophocolea bidentata (L.) Dum.	*Lop bid*	r	(2)	.		r	(2)	.		.	
Pleurozia purpurea Lindb.	*Ple pur*	3	(242)	+	(12)	3	(202)	1	(22)	r	(1)
Aneura pinguis (L.) Dum.	*Ane pin*	r	(18)	r	(2)	r	(13)	r	(1)	.	
Riccardia latifrons (Lindb.) Lindb.	*Ric lat*	r	(25)	.		r	(21)	r	(2)	.	
Sphagnopsida											
Sphagnum palustre L.	*Sph pal*	r	(3)	.		r	(3)	.		.	
Sphagnum papillosum Lindb.	*Sph pap*	2	(178)	4	(18)	2	(142)	1	(13)	.	
Sphagnum imbricatum Russ.	*Sph imb*	r	(2)	2	(1)	r	(1)	.		.	
Sphagnum magellanicum Brid.	*Sph mag*	r	(6)	r	(1)	r	(4)	.		.	
Sphagnum subnitens Russ. & Warnst. Ex (Warnst.)	*Sph sub*	r	(37)	2	(2)	r	(32)	r	(1)	.	
Sphagnum rubellum Wils.	*Sph rub*	7	(217)	41	(29)	4	(181)	r	(5)	.	
Sphagnum auriculatum Schimp.	*Sph aur*	+	(51)	.		r	(24)	4	(16)	13	(8)
Sphagnum cuspidatum Hoffm.	*Sph cus*	r	(30)	.		r	(18)	r	(6)	1	(3)
Sphagnum pulchrum (Braithw.) Warnst.	*Sph pul*	r	(4)	.		r	(4)	.		.	
Sphagnum tenellum (Brid.) Brid.	*Sph ten*	2	(237)	2	(16)	2	(200)	1	(18)	.	
Sphagnum compactum (DC in Lamarck & De Candolle)	*Sph com*	r	(3)	.		r	(3)	.		.	
Bryopsida											
Campylopus atrovirens var. atrovirens (De Not.)	*Cam atr*	+	(105)	r	(5)	+	(83)	2	(15)	r	(1)
Leucobryum glaucum (Hedw.) Ångstr.	*Leu gla*	r	(9)	.		r	(9)	.		.	
Racomitrium lanuginosum (Hedw.) Brid.	*Rac lan*	10	(263)	14	(21)	11	(213)	2	(23)	r	(1)
Breutelia chrysocoma (Hedw.) Lindb.	*Bre chr*	r	(11)	r	(3)	r	(8)	.		.	
Thuidium tamariscinum (Hedw.) Br. Eur.	*Thu tam*	r	(3)	.		r	(3)	.		.	
Campylium elodes (Lindb.) Kindb.	*Cam elo*	r	(1)	.		r	(1)	.		.	
Calliergon cordifolium (Hedw.) Kindb.	*Cal cor*	r	(1)	.		.		.		.	
Brachythecium rutabulum (Hedw.) Br. Eur.	*Bra rut*	r	(2)	.		r	(2)	.		.	
Pseudoscleropodium purum (Hedw.) Fleisch	*Pse pur*	r	(2)	.		r	(2)	.		.	
Hypnum jutlandicum (Holmen & Warncke)	*Hyp jut*	+	(113)	3	(26)	r	(84)	r	(1)	.	
Rhytidiadelphus squarrosus (Hedw.) Warnst.	*Rhy squ*	r	(12)	.		r	(12)	.		.	
Pleurozium schreberi (Brid.) Mitt.	*Ple sch*	r	(1)	.		r	(1)	.		.	

	Code	All	(336)	HU	(31)	HL	(259)	LL	(29)	HO	(10)
Gymnospermae											
Pinus sylvestris L.	*Pin syl*	r	(2)	r	(1)	r	(1)	.		.	
Angiospermae											
Caltha palustris L.	*Cal pal*	r	(3)	.		r	(3)	.		.	
Myrica gale L.	*Myr gal*	r	(7)	.		r	(7)	.		.	
Rumex acetosa L.	*Rum ace*	r	(2)	.		r	(2)	.		.	
Drosera rotundifolia L.	*Dro rot*	r	(167)	r	(16)	r	(127)	r	(15)	r	(2)
Drosera anglica Huds.	*Dro ang*	r	(18)	.		r	(9)	r	(6)	r	(2)
Drosera intermedia Hayne	*Dro int*	r	(32)	r	(1)	r	(14)	+	(12)	r	(2)
Calluna vulgaris (L.) Hull	*Cal vul*	6	(249)	14	(26)	6	(201)	+	(15)	r	(1)
Erica tetralix L.	*Eri tet*	4	(297)	5	(28)	5	(239)	2	(22)	r	(2)
Potentilla erecta (L.) Raeusch.	*Pot ere*	+	(40)	r	(4)	+	(35)	r	(1)	.	
Polygala serpyllifolia Hosé	*Pol ser*	r	(91)	r	(10)	r	(79)	r	(2)	.	
Angelica sylvestris L.	*Ang syl*	r	(1)	.		r	(1)	.		.	
Menyanthes trifoliata L.	*Men tri*	r	(17)	r	(2)	r	(8)	r	(2)	6	(4)
Pedicularis sylvatica L.	*Ped syl*	r	(31)	r	(3)	r	(27)	r	(1)	.	
Pinguicula lusitanica L.	*Pin lus*	r	(8)	.		r	(7)	r	(1)	.	
Pinguicula grandiflora Lam.	*Pin gra*	r	(4)	.		r	(4)	.		.	
Utricularia minor L.	*Utr min*	r	(2)	.		.		.		3	(2)
Hieracium sp. L.	*Hierac*	r	(3)	.		r	(3)	.		.	
Juncus acutiflorus Ehrh. ex Hoffm.	*Jun acu*	r	(7)	.		r	(7)	.		.	
Juncus effusus L.	*Jun eff*	r	(3)	.		r	(3)	.		.	
Eriophorum angustifolium Honck.	*Eri ang*	2	(267)	2	(23)	2	(206)	2	(27)	2	(7)
Eriophorum vaginatum L.	*Eri vag*	r	(82)	r	(7)	+	(74)	r	(1)	.	
Trichophorum cespitosum (L.) Hartm.	*Tri cae*	+	(119)	r	(9)	+	(104)	r	(5)	.	
Schoenus nigricans L.	*Sch nig*	1	(112)	1	(7)	2	(87)	1	(11)	r	(2)
Rhynchospora alba (L.) Vahl	*Ryn alb*	2	(158)	r	(9)	2	(110)	6	(28)	+	(5)
Rhynchospora fusca (L.) W.T. Aiton fil.	*Rhy fus*	r	(2)	.		.		.		r	(1)
Carex panicea L.	*Car pan*	r	(17)	.		r	(16)	r	(1)	.	
Carex limosa L.	*Car lim*	r	(40)	r	(2)	r	(25)	r	(3)	+	(6)
Holcus lanatus L.	*Hol lan*	r	(1)	.		r	(1)	.		.	
Agrostis stolonifera L.	*Agr sto*	r	(3)	.		r	(3)	.		.	
Molinia caerulea (L.) Moench	*Mol cae*	13	(325)	15	(31)	14	(258)	4	(26)	r	(4)
Narthecium ossifragum (L.) Huds.	*Nar oss*	3	(254)	2	(22)	3	(194)	2	(27)	2	(4)
Lichens	*Lichens*	r	(95)	r	(9)	r	(83)	r	(2)	.	

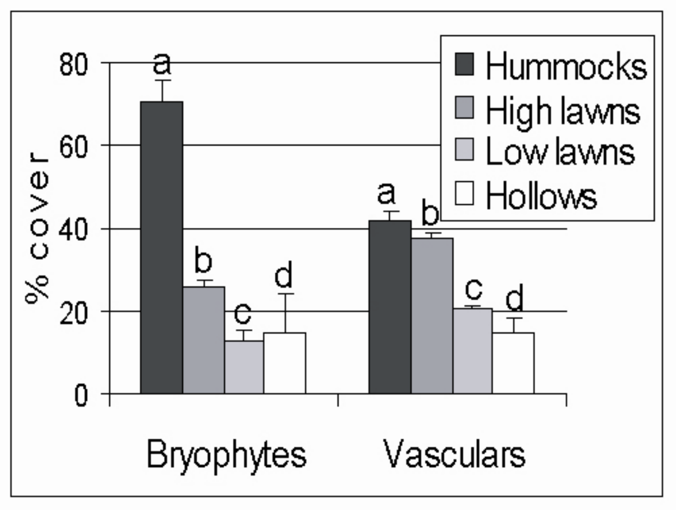


Figure 4.1. Mean percentage cover and standard error of bryophytes and vascular plants in the different microform types. Bars with different letters indicate that plant groups are statistically different (P < 0.05, Mann Whitney test following a Kruskal-Wallis test) between microform types.

9 % of the surveyed sample plots were identified as hummocks. These highest microforms were typically only a few tens of centimetres above the water table. Hummocks were relatively round in shape, with a diameter ranging between 50 and 100 cm. The bryophyte cover on hummocks was about 71 %, mainly composed of *S. rubellum* or *R. lanuginosum*. Hummocks were mostly covered by herbaceous plants (19 %), mainly *M. caerulea*, and by ericaceous shrubs (*C. vulgaris* and *E. tetralix*).

The flat areas at intermediate water table, i.e. lawns, were divided into high and low because the vegetation in low lawns was both shorter and less dense by comparison with high lawn vegetation (Laine et al., 2006). High lawns were by far the most common microform, covering 77 % of the bog area. The dominant vascular plant in high lawns was *M. caerulea*. High covers were observed also for *C. vulgaris* and *E. tetralix* while *R. lanuginosum* was the most abundant bryophyte.

Low lawns were much less frequent than high lawns, occurring only in 9 % of the sample plots. Among the vascular plants, *Rhynchospora alba* occurred very frequently, while *S. auriculatum*, *R. lanuginosum* and *Campylopus atrovirens var. atrovirens* had the highest bryophyte coverage.

The wettest microforms, hollows, were completely submerged by standing water for most of the year. Hollows were fairly oblong in shape, ranging between 50 and 300 cm in length. Only 3 % of the sample plots belonged to this microform type. Two forms of hollows occurred: hollows completely covered by mosses or by a mud bottom. In both cases, the plant communities were very small and variable, with bryophytes and vascular plants both having a mean cover of about 15 %. The most abundant and frequent moss species was *S. auriculatum*, while *Menyanthes trifoliata* and *Utricularia minor* had the highest vascular plant covers.

4.4.2 Soil water chemistry and water table

Water chemistry showed little variation between microforms across the blanket bog (Table 2). The pH ranged between 4.28 and 5.14 with hummocks and high lawns having a significantly lower pH than hollows. The corrected conductivity varied little among different microform types, averaging at 46.7 $\mu S\ cm^{-1}$. Na^+, Ca^{2+}, NH_4^+ and TON were higher on average in the drier than in the wetter microforms, but no statistically significant difference was discovered. SO_4^{2+}, which ranged between 0.64 and 3.81 $mg\ l^{-1}$, had significantly higher concentrations in high lawns than in low lawns and hollows. Cl^- concentrations and water colour didn’t show any clear trend between the different microform types.

The water table ranged between 27 cm above and 22 cm below the soil surface for the highest and between 0 and 40 cm below the surface for the lowest level (Table 2). The high water table measurements significantly differed among all microforms, while the lowest water table estimates significantly differed only between the highest and lowest microforms only. The peat depth ranged between 55 and > 200 cm, being over 200 cm for 65% of the measured points.

	Weighted average of all microforms	Hummocks (n = 20)	High lawns (n = 42)	Low lawns (n = 15)	Hollows (n = 9)
pH	4.53 (0.13)	4.54^{a} (0.14)	4.51^{a} (0.12)	4.59^{ab} (0.15)	4.75^{b} (0.25)
Kcorr (µS cm^{-1})	46.7 (5.3)	46.0^{a} (4.5)	46.8^{a} (5.3)	46.5^{a} (6.4)	46.5^{a} (4.8)
Na^{+} (mg l^{-1})	6.70 (1.20)	6.38^{a} (0.92)	6.78^{a} (1.35)	6.33^{a} (0.45)	6.31^{a} (0.52)
Ca^{+} (mg l^{-1})	0.76 (0.43)	0.93^{a} (0.56)	0.74^{a} (0.41)	0.76^{a} (0.49)	0.66^{a} (0.37)
Cl^{-} (mg l^{-1}l)	8.89 (1.20)	8.64^{a} (1.25)	8.94^{a} (1.22)	8.81^{a} (1.21)	8.69^{a} (0.69)
SO$_4^{2-}$ (mg l^{-1})	1.93 (0.50)	1.86^{ab} (0.47)	2.00^{a} (0.50)	1.60^{b} (0.54)	1.48^{b} (0.49)
NH$_4^{+}$ (mg N l^{-1})	0.042 (0.047)	0.039^{a} (0.033)	0.044^{a} (0.053)	0.027^{a} (0.017)	0.023^{a} (0.012)
TON (mg N l^{-1})	0.019 (0.060)	0.011^{a} (0.022)	0.022^{a} (0.072)	0.005^{a} (0.005)	0.006^{a} (0.006)
Colour (Hazen)	109 (68)	83^{a} (45)	113^{a} (72)	88^{a} (49)	123^{a} (76)
WThigh (cm)	-3.6 (4.2)	-10.7^{a} (6.1)	-4.0^{b} (4.1)	1.1^{c} (1.1)	11.9^{d} (7.8)
WTlow (cm)	-18.7 (6.9)	-22.9^{a} (7.0)	-20.2^{a} (7.0)	-6.5^{b} (5.4)	-3.2^{b} (7.0)

Table 4.2. Mean values (standard deviations in parenthesis) of soil water chemical variables and water tables in the different vegetation communities. The mean values followed by a different letter within a row were significantly different at $P < 0.05$ based on ANOVA and Tukey test (for SO$_4^{2-}$ and WTlow) or Kruskal-Wallis and Mann-Whitney tests (for pH and WThigh, when Levene's test was significant). WThigh = high water table; WTlow = low water table.

4.4.3 Ordination analyses

The first CCA explained the bryophyte distribution. This CCA showed that high water table and pH were the only significant measured environmental variables explaining the bryophyte distribution (Figure 4.2). Axis 1 was mainly composed of a moisture gradient. *S. auriculatum*, *Cladopodiella fluitans*, *S. cuspidatum* and *Campylopus atrovirens var. atrovirens* were grouped together at the wettest end of the water table, whereas *S. rubellum*, *Hypnum jutlandicum* and *M. anomala* were located in the driest areas. Axis 2 was mostly composed of a pH gradient. *Cephalozia* spp. and *K. pauciflora* had their optimum at lower pH than the other bryophytes, while *Diplophyllum albicans* and *S. subnitens* were located in less acidic areas.

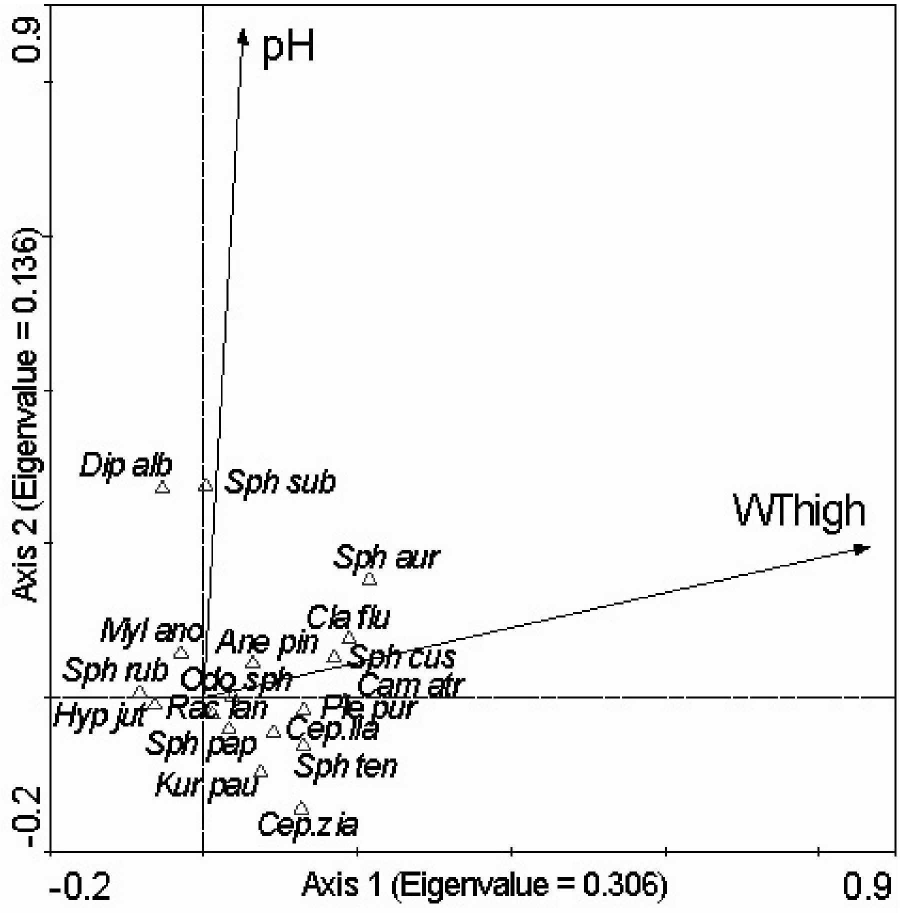


Figure 4.2. Partial CCA ordination showing the distribution of bryophyte species in relation to high water level (WThigh) and pH. The proximities of the peatland borders were standardized by using the distances to the peatland borders as covariables. See Table 1 for the complete species names. Axis 1 (P = 0.002) explained 8.6 % of the species data and axis 2 (P = 0.006) 3.9 %. The inter set correlations of WThigh with axis 1 was 0.74. The inter set correlations of pH with axis 2 was 0.51.

The second CCA explained the vascular plant distribution. This CCA showed that the distribution of vascular plants was significantly explained only by high and low water tables and peat depth, among the measured environmental parameters (Figure

4.3). Axis 1 was mainly a combination of high and low water tables and suggests that *M. trifoliata*, *Drosera anglica*, *D. intermedia* and *Carex limosa* were located in the wettest, whereas *Potentilla erecta* and *Pedicularis sylvatica* were in the driest areas of the bog. Axis 2 was mostly composed of a peat depth gradient. *Trichophorum cespitosum*, *P. erecta* and *Pedicularis sylvatica* were centred at the shallowest peat depth.

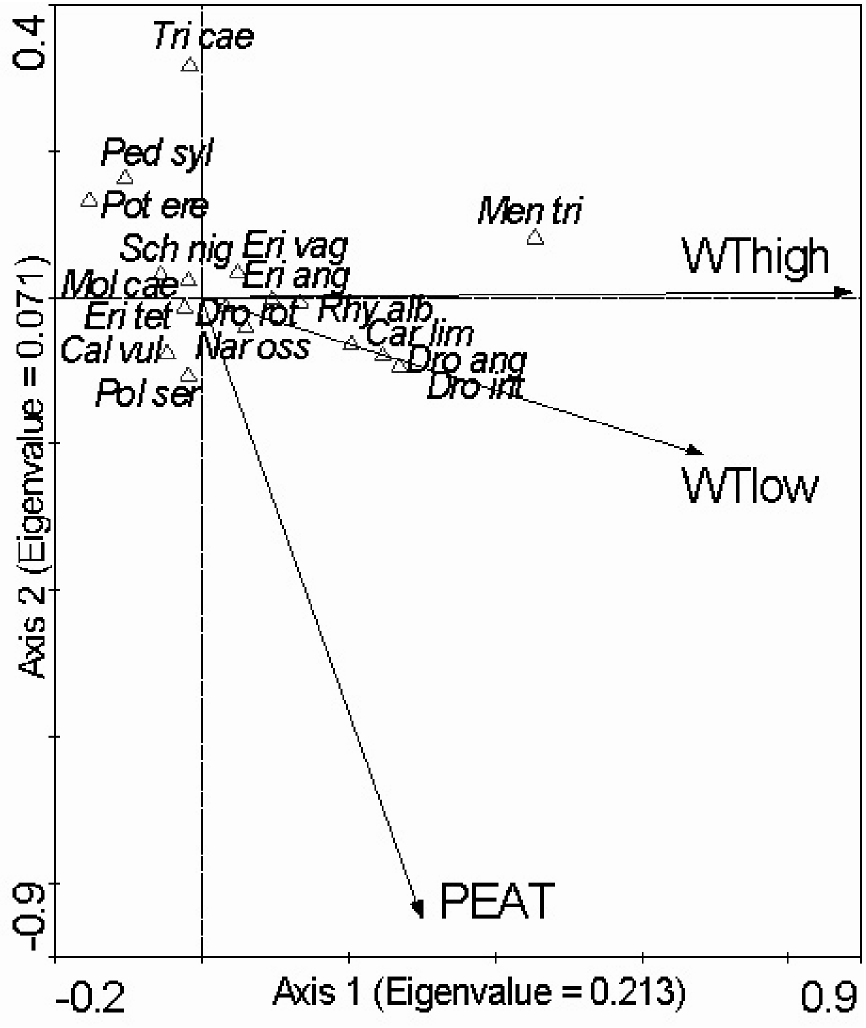


Figure 4.3. Partial CCA ordination showing the distribution of vascular species in relation to high (WThigh) and low water tables (WTlow) and peat depth (PEAT). The proximities of the peatland borders were standardized by using the distances to the peatland borders as covariables. See Table 1 for the complete species names. Axis 1 (P = 0.002) explained 8.5 % of the species data and axis 2 (P = 0.022) 2.8 %. The inter set correlations of WThigh and WTlow with axis 1 were 0.70 and 0.58, respectively. The inter set correlations of PEAT with axis 2 was –0.45.

Since the water table, pH and peat depth were the only significant environmental parameters explaining the bryophyte and vascular plant distribution in the CCA, we used these variables in the GAM diagram analyses (Figure 4.4). The mean between the high and low water tables was used. As in the CCA, *S. auriculatum*, *Campylopus atrovirens* var. *atrovirens* and *M. trifoliata* had their optimum at high water table, while *S. rubellum*, *H. jutlandicum* and *P. erecta* had their optimum at low water table (Figures 4.4a and 4.4b). *R. lanuginosum*, *S. papillosum* and *M. caerulea* also had their highest occurrence in the driest areas of the peatland, but they showed a wider tolerance to moisture conditions. *E. tetralix* and *C. vulgaris* had their optimum at water table averages between 10 and 20 cm below the soil surface, while *N. ossifragum* and *R. alba* peaked at mean water tables between 0 and 10 cm below the peat surface. Along the pH gradient, *S. subnitens* and *D. albicans* showed a narrow optimum at high pH (Figure 4.4c) as suggested by the CCA diagram. Although they had a wide habitat range, *S. auriculatum* peaked in areas with higher pH, while *S. tenellum* and *K. pauciflora* had their optimum in areas with lower pH. As indicated by the CCA, *P. erecta* and *T. cespitosum* were more abundant on shallow peat. *M. caerulea* and *N. ossifragum* showed a wide tolerance to peat depth, with *M. caerulea* having an inclination for shallower while *N. ossifragum* for deeper peat (Figure 4.4d).

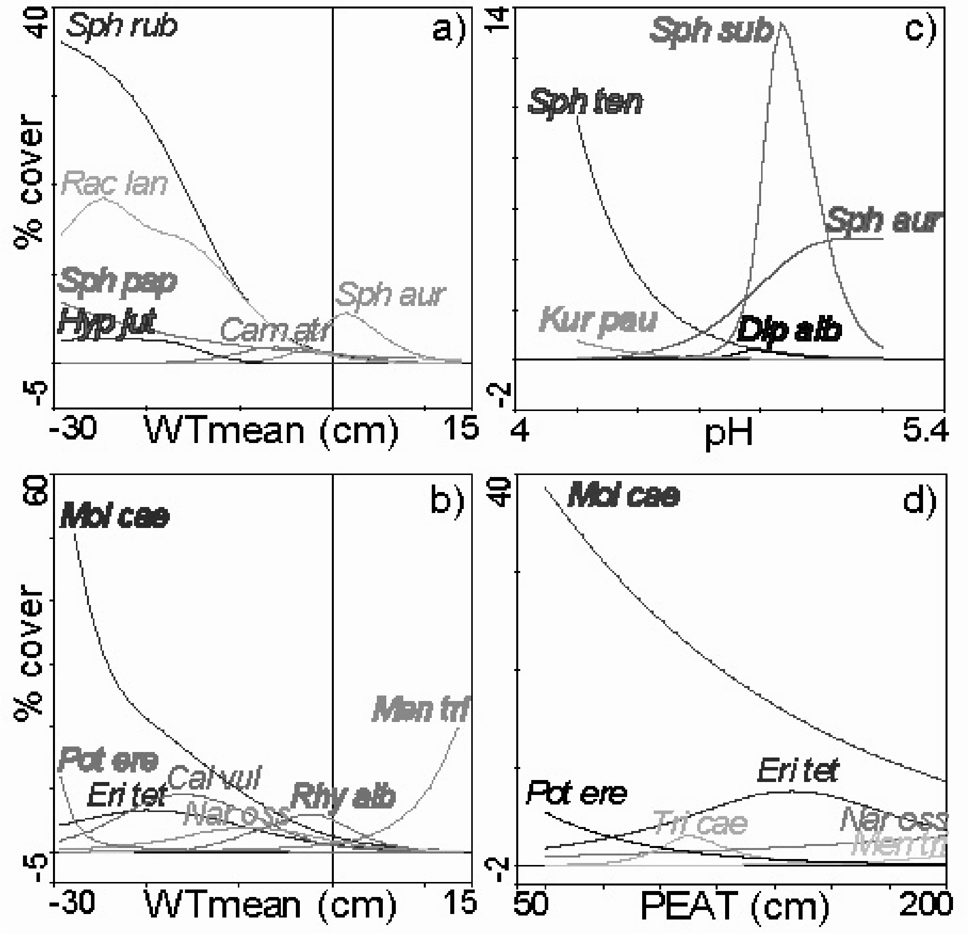
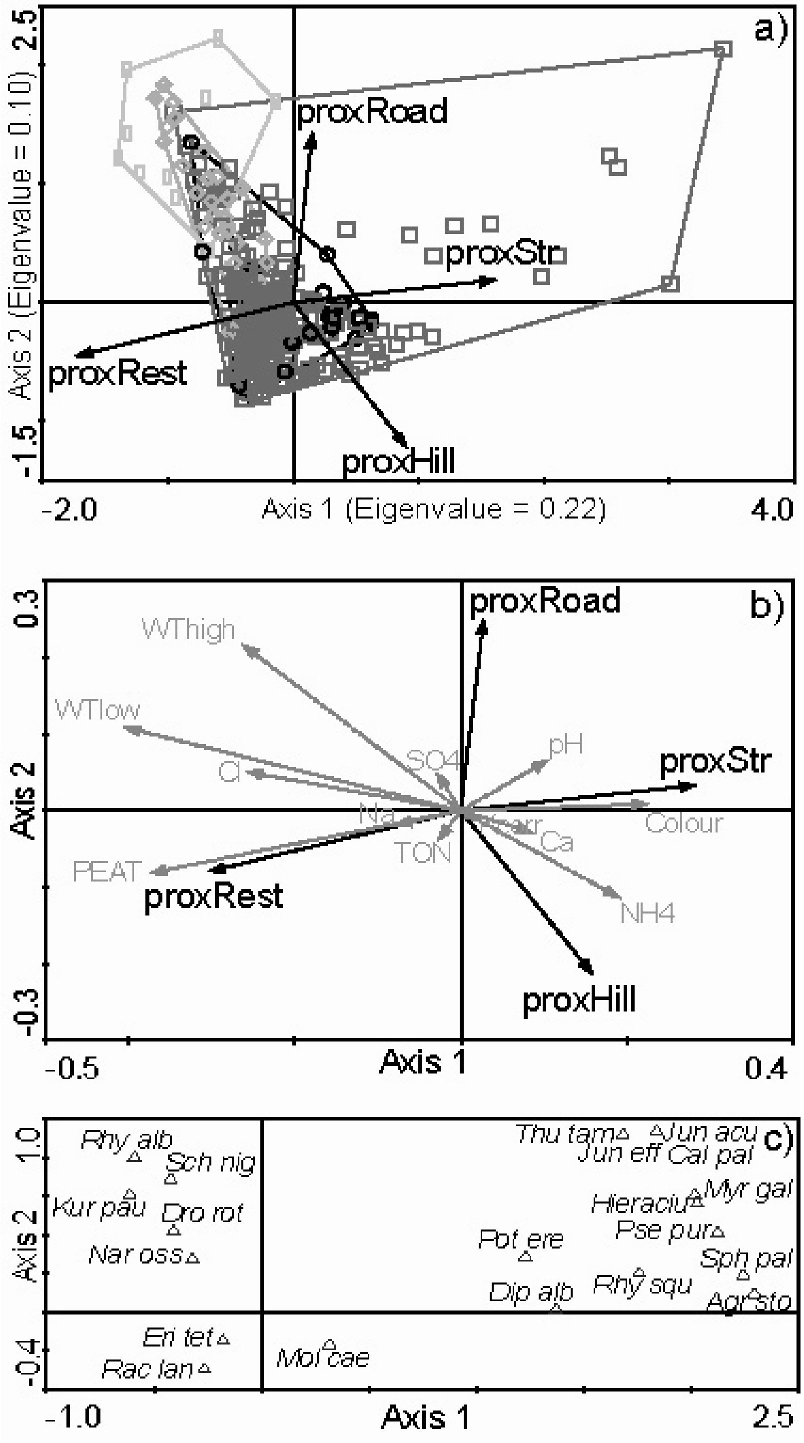


Figure 4.4 Response of plant species to (a, b) mean water table (WTmean), (c) pH and (d) peat depth. General Additive Models were used to estimate the response of the most common species. Only species having a significant ($P < 0.05$) response to the environmental variables are shown. See Table 1 for species complete names.

The CCA focusing on the effect of peatland borders indicated a rather homogeneous distribution of different vegetation communities across the bog. Most of the plots overlapped in the centre of the ordination diagram, suggesting that there is little variation among plant communities regarding their distance from the peatland margins (Figure 4.5a). The only communities clearly departing from the others were the high lawns plots surveyed close to the natural stream border and the low lawns and hollows close to the road. The high lawns close to the stream were displayed at some distance from the other high lawns, stretched along the right hand-side of axis 1. This suggests that the area close to the stream is covered by high lawns, which have substantial variation between them in addition to being different from high lawns in other areas of the bog (Figure 4.5a). The area along the stream appears to be correlated with lower water table, shallower peat depth, lower concentrations of Cl^-, higher concentrations of NH_4^+, and higher water colour and pH than other peatland areas (Figure 4.5b). The vascular flora along the stream was composed of *Myrica gale* and *P. erecta*, together with plant species usually found in marshes and wet meadows, such as *Caltha palustris*, *Juncus acutiflorus*, *J. effusus* and *Agrostis stolonifera* (Figure 4.5c). The bryophyte vegetation was characterized by a rich flora uncommon in other parts of the bog, consisting of *D. albicans*, *Thuidium tamariscinum*, *S. palustre*, *Rhytidiadelphus squarrosus* and *Pseudoscleropodium purum* (Figure 4.5c). As with the high lawns close to the stream, also the hollows and low lawns show a clear variation compared to most of the other vegetation communities in the bog. This indicates that beside large areas of rather homogeneous high lawn vegetation, the peatland is covered by more heterogeneous vegetation, composed of a mixture of hollows, low lawns, high lawns and hummocks (Figure 4.5a). This area appears to be wetter than the rest of the peatland (Figure 4.5b) and not composed of specific flora (Figure 4.5c).

Figure 4.5 (next page). CCA ordination showing the distribution of a) different microforms, b) environmental variables and c) plant species in relation to distance from peatland boarders. Only species with at least 5 % variability explained by the CCA axes are shown. Axis 1 (P = 0.004) explained 2.9 % of the samples data and axis 2 (P = 0.022) explained 1.3 %. The inter set correlations of proxRest and proxStre with axis 1 were –0.43 and 0.40 respectively. The inter set correlations of proxRoad and proxHill with axis 2 were 0.42 and –0.36.

proxRest = proximity to the restoration area border; proxStre = proximity to the stream; proxRoad = proximity to the road; proxHill = proximity to the hill-grazing area. Microforms are indicated with different signs: O for HU, □ for HL, ◊ for LL, ▯ for HO. WThigh = high water table; WTlow = low water table; PEAT = peat depth. See Table 1 for species complete names.


a)
2.5
Axis 2 (Eigenvalue = 0.10)
-1.5
-2.0
Axis 1 (Eigenvalue = 0.22)
4.0
proxRoad
proxStr
proxRest
proxHill
b)
0.3
Axis 2
-0.3
-0.5
Axis 1
0.4
proxRoad
WThigh
WTlow
SO4
pH
proxStr
Cl
Na
Colour
TON
Ca
PEAT
proxRest
NH4
proxHill
c)
1.0
Axis 2
-0.4
-1.0
Axis 1
2.5
Rhy alb
Sch nig
Kur pau
Dro rot
Nar oss
Eri tet
Rac lan
Mol cae
Thu tam
Jun acu
Jun eff
Cal pal
Hieraciu
Myr gal
Pse pur
Pot ere
Sph pal
Dip alb
Rhy squ
Agr sto

4.5 Discussion

4.5.1 General nature of the peatland

The plant communities observed in this study closely resemble those previously described for Atlantic blanket bogs in Ireland and Scotland (Doyle & Moore, 1978; Doyle, 1982; Doyle, 1990). Hummocks and lawns in the study site are likely to belong to the phytosociological association taxon of the *Pleurozio purpurea-Ericetum tetralicis*, described for deep-peat ombrotrophic blanket bogs, due to the presence of the characteristic species *Schoenus nigricans*, *Pleurozia purpurea* and *Campylopus atrovirens* (Doyle, 1990). The hollows occurring in the study site are likely to belong to the *Sphagno-Rhynchosporetum tenelli* taxon, one of the two hollow vegetation associations typical of Atlantic blanket bogs, due to the presence of the characteristic species *Rhynchospora fusca* and *Sphagnum cuspidatum* (Doyle, 1990). The vegetation close to the stream resembles the *Myrica gale* dominated vegetation described along drainage channels in Atlantic blanket bogs (Doyle, 1990). Our results are in good agreement with Doyle (1990), who suggested that this vegetation colonises shallow peat areas near streams and drains, where water movement occurs in seepage and occasional inundation causes additional nutrient input.

Differences in water sampling procedures can complicate the comparison of water chemistry between different peatlands (Tahvanainen & Tuomala, 2003). Even with this limitation, a comparison of the chemical analyses suggests that the water chemistry in Glencar is similar to other Atlantic blanket bogs, even if with slightly lower ion concentrations (Proctor, 1992; Shotyk, 1997). pH, corrected conductivity and the concentrations of ions of marine origin (Na^+ and Cl^-) were relatively high, higher than in Montane blanket bogs (Adamson et al., 2001; Proctor, 2006), boreal poor fens and bogs (Vitt & Chee, 1990; Vitt et al., 1995; Wind-Mulder et al., 1996; Tahvanainen et al., 2002). The land origin ion Ca^{2+} had similar concentrations as in Montane blanket bogs (Adamson et al., 2001; Proctor, 2006), but typically lower than in boreal poor fens and bogs (Vitt & Chee, 1990; Vitt et al., 1995; Tahvanainen et al., 2002). Concentrations of SO_4^{2-} were generally lower in Glencar than in a Montane blanket bog (Adamson et al., 2001) and Canadian boreal bogs

(Wind-Mulder et al., 1996), but higher than in a Finnish boreal fen complex (Tahvanainen et al., 2002). NH_4^+ had slightly lower concentrations than in a Montane blanket bog (Adamson et al., 2001) and typically higher than in a boreal fen in Canada (Vitt & Chee, 1990) but lower than in a Finnish boreal fen complex (Tahvanainen et al., 2002). Similar to vegetation composition, the water chemistry suggests the general ombrotrophic character of the site.

4.5.2 Variation in vegetation in relation to environment

The bryophyte cover in the study site decreases sharply from 71 % in hummocks to about 25 % in high lawns and less in the wetter microforms (Figure 4.1). The bryophyte cover in blanket bogs is very low compared to other ombrotrophic bogs (e.g. Glaser et al., 1990); in Glencar this is due to the paucity of hummocks (only 9 % cover) and to the scarcity of mosses in lawns. *Sphagnum* species in the study site are generally restricted to either the driest microform, as is *S. rubellum*, or to the wettest, as are *S. auriculatum* and *S. cuspidatum* (see Table 1). Vascular plants have a higher occurrence in high lawns and hummocks (Figure 4.1). Yet, even if with different coverage, most vascular species (e.g. *Eriophorum angustifolium*, *Narthecium ossifragum*, *Molinia caerulea*, *Erica tetralix* and *S. nigricans* (Table 1)) do not appear to be as restricted to certain microforms as bryophytes.

Many studies suggest that the vegetation distribution in peatlands is mostly controlled by water table, chemical status and distance from the peatland margins (e.g. Malmer, 1986). The ordination solutions suggest that the water table is the variable that best explains the distribution of the plant species (Figures 2, 3, 4a and 4b). The separate analyses for bryophytes and vascular species, which revealed a different secondarily control after water table (pH gradient for bryophyte and peat depth for vascular plant distributions, Figures 2, 3, 4c and 4d) agree with some previous studies (Vitt & Chee, 1990; Bubier, 1995). Vitt & Chee (1990) found that the distribution of bryophytes between different boreal fen types in Western Canada followed a pH and mineral content gradient, while a nutrient gradient was more important for the distribution of vascular plants.

4.5.3 The role of margins

The CCA focusing on the effect of peatland margins indicated that there is little variation in the vegetation between the central part of the bog and its artificial edges (hill-grazing and restoration areas), but a substantial variation related to the distance from the stream (Figure 4.5a). The distance from the natural margins is recognised to be one of the drivers of northern peatland vegetation patterns (Malmer, 1986), but acknowledged as being unclear and caused by different and varying local effects (Wheeler & Proctor, 2000; Økland et al., 2001). The area near the stream in the Glencar Atlantic blanket bog appears well defined: it is an area with high vegetation biodiversity, characterized by shallower peat depth, where the water table drops considerably below the peat surface, is richer in NH_4^+, has lower concentrations of Cl^- but higher pH and water colour than other areas in the bog (Figure 4.5b). On the other hand, since the blanket bog appears homogeneous close to disturbed areas, we can conclude that the influence of any human or animal disturbance on the blanket bog is restricted to the margins. Besides, since the CCA diagram displayed the wettest microforms separately from most of the driest microforms (Figure 4.5a), it also suggests the existence of a peatland surface pattern of either a heterogeneous mixture of microforms or a homogeneous high lawn vegetation cover.

4.5.4 Carbon and climate change

In recent years the interest in carbon fluxes in peatlands has increased since the large carbon reservoirs of peat soils are potentially available to the atmosphere if decomposition exceeds production (Bubier et al., 1995) due to climate change. Carbon fluxes have been measured since 2002 in the Glencar Atlantic blanket bog (see Sottocornola & Kiely, 2005). Previous work in the same study site has showed that areas composed of different vegetation communities have different CO_2 flux patterns, with drier microforms having higher rates of CO_2 uptake than the wetter communities (Laine et al., 2006). This different CO_2 flux pattern likely coincides with the surface patterning variation of either the mixture of microforms or homogeneous high lawn vegetation cover (Figure 4.5a). In the same way, the vegetation variation related to the distance from the stream suggests the possible existence of a different carbon flux pattern between this natural border area and the other peatland sectors, as previously observed by Waddington & Roulet (1996).

Chamber measurements carried out in the study site (Laine et al., in press) found that vegetation communities at a median summer water table depth of 12 cm below the soil surface were those with the highest CO_2 uptake. Continuous measurements of water table in the study site (see Sottocornola & Kiely, 2005) reveal that the mean and median water table in the August-December 2005 period was within a few cm of the mean and median water table during the period of the study by Laine *et al.* (in press) suggesting that a comparison between the water tables measured in the two studies is possible. The vegetation at locations with water table average of 10-15 cm below the soil surface is dominated by *M. caerulea*, *E. tetralix*, *Calluna vulgaris*, *N. ossifragum*, *S. rubellum* and *Racomitrium lanuginosum* (Figures 4a and 4b), which are therefore likely to be the species responsible for the highest CO_2 uptake in the study site. Climate change could affect blanket bogs if the predicted precipitation pattern change occurs in maritime regions (Moore, 2002). Ellis & Tallis (2000) predicted a strong impact of climate change on Atlantic blanket bogs, based on pollen and macrofossils evidences. Climate change scenarios for Ireland predict warmer temperatures with a decrease in precipitation in summer and an increase in winter (McGrath et al., 2005), a trend that has been detected in the west of the country from the mid-1970s (Hoppe & Kiely, 1999; Kiely, 1999). A decrease in water table is expected to cause a decrease in pH (Laine et al., 1995). Lower pH and summer water table would possibly increase the occurrence of *S. rubellum*, *S. papillosum*, *R. lanuginosum*, *M. caerulea*, *Potentilla erecta* and ericaceous shrubs (Figures 2, 3 and 4), while species typical of drier communities would probably invade drying shallow hollows (Strack et al., 2006). Since the development of a vegetation surface patterning seems to be associated with high wetness (Figure 5b, Foster et al., 1988; Svensson, 1988), the drop in water table expected with climate change might promote the spread of a homogeneous high lawn vegetation over the wettest parts of the ecosystem, enhancing the CO_2 uptake in these areas (Laine et al., 2006). However, since the carbon fluxes are strongly linked with water table (Laine et al., 2007), climate change is expected to modify the present carbon flux patterns at the ecosystem level, through hydrological, chemical and vegetation change, and possibly reducing the ecosystem carbon uptake ability.

4.6 Conclusions

The Glencar peatland is typical of Atlantic blanket bogs in the maritime regions of Northwest Europe, in terms of both vegetation and water chemistry. Our study identifies the influence of centre-natural margin gradients on the vegetation pattern and indicates that the edges of an Atlantic blanket bog effectively buffer human and animal disturbances. These findings suggest that small pristine blanket bogs are also worthy of conservation and that such measures should include sectors close to the natural peatland borders, where a distinct vegetation, rich in biodiversity, is likely to occur.

Climate change is expected to cause a decrease in summer water table and pH in Atlantic blanket bogs. Since bryophytes seem to have a narrower niche than vascular plants, and since their distribution is linked to both water table and pH, it is likely that climate change will affect bryophyte composition more than that of vascular plants. Even if carbon uptake may increase in some wetter areas of the ecosystem, overall the carbon uptake in Atlantic blanket bogs is expected to decrease due to the hydrological, chemical and vegetation modifications that will occur as a consequence of climate change.

Acknowledgement

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An Atlantic Blanket Bog is a modest CO_2 sink

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5.1 Abstract

Northern peatlands contain 1/3 of the world's soil carbon pool. Blanket bogs are peatlands that occur in maritime regions where precipitation is much greater than evapotranspiration. The role of blanket bogs in C dynamics has not been quantified. We describe an investigation of CO_2 fluxes using an eddy covariance (EC) system in a pristine Atlantic blanket bog in Ireland during 2003 and 2004. This is the first multiyear study using EC techniques in a blanket bog.

We found that the bog ecosystem was a CO_2 sink for five months in each year. The annual CO_2 flux had a sink magnitude of -49 (2003) and -61 g C m^{-2} (2004). These magnitudes are similar to boreal raised bogs, while higher values have been reported for boreal fens and lower for subarctic fens.

5.2 Introduction

Although Northern peatlands are generally of low productivity, they are important ecosystems because they contain up to 1/3 (455 Gt of C) of the world's estimated soil carbon (C) pool (Gorham, 1991). The future of this C reservoir is of key interest as many regions (e.g. the arctic tundra) have already undergone a C status change from sink to source due to global warming (Oechel et al., 2000), with an additional risk of a positive feedback. Climate warming is expected in peatlands to affect the hydrology (Roulet et al., 1992), the vegetation zones and plant composition (Weltzin et al., 2003): all factors influencing the C dynamics. For Ireland, McGrath et al. (2005) predict mean monthly temperature increase between 1.25 and 1.5 °C, a decrease in precipitation in summer and an increase in winter for the period 2021-2060.

Many C flux studies have been carried out using the eddy covariance (EC) system during the peatland growing season only (e.g. Shurpali et al., 1995; Suyker et al., 1997) and more recently for the full year (e.g. Lafleur et al., 2001b; Aurela et al., 2002). Some peatlands have been found to be net sources of CO_2 (Lafleur et al., 1997), others were found to be net sinks CO_2 (Suyker et al., 1997; Nordstroem et al., 2001; Friborg et al., 2003; Lafleur et al., 2003; Aurela et al., 2004), while others were found to be a sink in one year and a source in another year (Shurpali et al., 1995; Joiner et al., 1999; Arneth et al., 2002).

Studies of C dynamics in peatlands have been carried out mostly in boreal bogs and fens and in sub-arctic fens (e.g. Suyker et al., 1997; Waddington & Roulet, 2000; Friborg et al., 2003; Lafleur et al., 2003; Aurela et al., 2004), some in arctic fens (e.g. Nordstroem et al., 2001) but very few studies of CO_2 fluxes have been performed in blanket bogs (Beverland et al., 1996; Chapman & Thurlow, 1996). To our knowledge, no CO_2 measurements have been performed using the EC method on an Atlantic blanket bog over the full calendar year.

Blanket bogs are ombrotrophic peatlands receiving water and nutrients only from atmospheric depositions. These ecosystems are usually in flat to moderately sloping terrain with an oceanic climate.

In the global context, blanket bogs are rare ecosystems, accounting only for ca. 3% of the world peatland area (Foss et al., 2001). However, locally they are important, not only for biodiversity reasons but particularly for their role in the C balance of regions. In Ireland, out of 1.34 million of hectares covered by peatlands (~16% of the land area), about 240,000 ha are blanket bogs (Hammond, 1981). The role of this regionally large ecosystem in C dynamics has not been quantified.

The objective of this study is to quantify the CO_2 source/sink status of an Atlantic blanket bog over two calendar years using the EC technique.

5.3 Site Description

The experimental site is an Atlantic blanket bog located at Glencar, County Kerry, in Southwest Ireland (Latitude: 51° 55' N, Longitude: 9° 55' W) at an elevation of approximately 150 m above sea level. The characteristic feature of the bog is a spatially heterogeneous surface, with a mosaic of microforms, which differ in relative altitude, plant composition and water table level. We divided these microforms into four classes based on relative elevation: hummocks (*HU*), high lawns (*HL*), low lawns (*LL*) and hollows (*HO*). The elevation difference between the highest (*HU*) and lowest (*HO*) microform is typically 20 to 40 cm. *HO* are depressions covered by water and hollow vegetation. The microform composition inside the EC footprint was estimated as 4% (*HU*), 58% (*HL*), 25% (*LL*) and 13% (*HO*) (Laine et al., 2006). The most common plants occurring in the bog are *Molinia caerulea* (purple moor-grass), *Schoenus nigricans* (black-top sedge), *Rhynchospora alba* (white beak-sedge), *Erica tetralix* (cross-leaved heath), *Calluna vulgaris* (common heather), *Eriophorum angustifolium* (common cotton grass), *Narthecium ossifragum* (bog asphodel) and *Menyanthes trifoliata* (buckbean). The bryophyte component is not widespread (less than 10% of the bog surface) and the dominant species include *Racomitrium lanuginosum* (wolly-hair moss) and *Sphagnum* spp. (bog mosses). The leaf area index (LAI), measured in 2005 with a PAR/LAI Ceptometer (LP-80 AccuPAR, Decagon devices, Inc., USA), was between 0.2 in winter and 0.7 $m^2 m^{-2}$ in summer. The peat depth is > 2 m in the EC footprint.

5.4 Methods

The experimental arrangement consists of a micrometeorological station and an EC system for CO_2 flux. The instrumentation is situated in the middle of the bog with at least 300 m of uninterrupted fetch on all sides of the EC station. The ground contours within the fetch are relatively flat. The flux footprint was estimated based on a fetch to sensor height ratio of 100:1 combined with the probability density distribution of the wind direction.

The micrometeorological equipment included a net radiometer (CNR 1, Kipp & Zonen, the Netherlands) and a sensor for Q, photosynthetically active radiation (PAR Lite, Kipp & Zonen, the Netherlands). Air temperature (T_a) was measured at 2 m height with a shielded probe (HMP45C, Vaisala, Finland), while soil temperature was recorded with a probe (107, Campbell Scientific, UK) at 20 cm below the *HL* vegetation (T_{soil}). Precipitation was measured with two tipping bucket rain gauges (an ARG100, Environmental Measurements Ltd., UK and an Obsermet OMC-200, Observator BV, The Netherlands). The water table (WT) depth was continuously measured with a pressure transducer (PCDR1830, Campbell Scientific, UK) placed inside a metal well, pierced all along its height. A malfunction of the WT transducer for the first 17 months of the experiment was corrected with interpolation from manual measurements (Laine et al., 2007). Signals from all the micrometeorological sensors were monitored every minute and averaged over a 30-minute period in a CR23X data logger (Campbell Scientific, UK).

The EC system consisted of a 3-D sonic anemometer (Model 81000, R.M. Young Company, USA) and an open-path CO_2/H_2O infrared gas analyser (LI-7500, LI-COR, USA) mounted 3 m above the *HL* vegetation. Data were recorded at 10 Hz and fluxes were Reynolds-averaged every half-hour. The 30-minute averaged EC CO_2 fluxes are defined as:

$$F_c \cong -\overline{w' \rho_c'} \tag{5.1}$$

where w' is the vertical wind velocity fluctuations [m s^{-1}] and ρ_c' the CO_2 density fluctuations (mmol m^{-3}). We adopted the micrometeorological convention in which fluxes from the biosphere to the atmosphere are positive. We report on the data collected for the two calendar years, 2003 and 2004.

In processing the data, raw EC flux data were double rotated, so that the mean horizontal wind speed was rotated into the mean wind direction and the mean vertical wind velocity was set to zero. The vertical rotation was based on the averaged 30-minute angle between the horizontal and vertical axes. In low wind speed conditions, the estimate of the vertical angle can signal unsatisfactory outputs and so fluxes that were rotated for unrealistic angles where rejected. The CO_2 flux was then corrected for variations in air density due to fluctuation in water vapor and heat flux (Webb et al., 1980). The flux data were partitioned into day and night sets, using a short-wave incoming radiation threshold of 10 W m^{-2}. With this threshold, 46% of the two-year dataset comprised of day data. No clear correlation was found between the friction velocity (u_*) and the dry night CO_2 fluxes and so we did not apply a u_* filter. Nighttime uptake values were rejected.

The time series of day and night fluxes were divided into twelve bimonthly bins over the two-year dataset and filtered for predetermined realistic threshold values for the season. Approximately 15% of the data in 2003 and 2004 were rejected during rainfall periods and within one hour after rain. After post-processing and filtering, 43.4% of the CO_2 flux data for 2003 (~60% day and 30% night data) and 50.6% for 2004 (~69% day and 35% night data) was good and suitable for further analysis. Most night data that was rejected was outside the growing season.

The gaps in the time series were filled with non-linear regression equations defined using the Curve Fitting Function of MATLAB 6.5 (MathWorks Inc., USA) software for monthly (May and June 2003, March and April 2004) or bimonthly periods. For day data, the best gap filling functions were rational functions of polynomials in one variable of different orders that relate the 30-minute CO_2 flux either with air temperature (January-February and May 2003, April 2004) or with Q (all other periods). For night data an exponential Q_{10} gap filling function was defined for the full two-year period and related the half hour flux with the 20 cm deep soil temperature.

In 2003, between Julian day 145 and 155 (25th May to 4th June) no data were logged due to an electricity outage. The missing meteorological data were replaced with the last 5 good days of data before the outage and the first 5 days of good data after the outage except for precipitation. Precipitation data were obtained from a comparison with the nearby Valentia weather station (~30 km west of the site, 51° 56' N, 10° 14' W) records. The EC system suffered a break, in 2003 between Julian day 141 and 177 (21st May to 26th June). The 36 days gap in the EC CO_2 flux was filled using gap filling equations based on meteorological measurements. Notably the missing May fluxes were determined with a function based on air temperature, defined for the first 21 good days of the month. The 26 missing flux days in June were calculated with a rational function of polynomials of degree one based on Q, derived from the averaging of the same type of function for May and July-August 2003.

5.5 Results

The photosynthetically active radiation (Figure 5.1a) followed the expected pattern, with the highest monthly average values (for the day hours) in June and the lowest in December. The daytime annual Q average was 482 (2003) and 458 µmol m^{-2} s^{-1} (2004). Precipitation was abundant and frequent throughout the year (Figure 5.1b). The total annual precipitation was 2510 mm (2003) and 2356 mm (2004). The monthly precipitation ranged between a low of 40 mm in August 2003 to a high of 540 mm in November 2003. In 2004 the monthly variation was less extreme than in 2003 with no month experiencing rainfall less than 95 mm. At the Valentia weather station the rainfall measured in both 2003 and 2004 was slightly below the 30-year average (1961-1990).

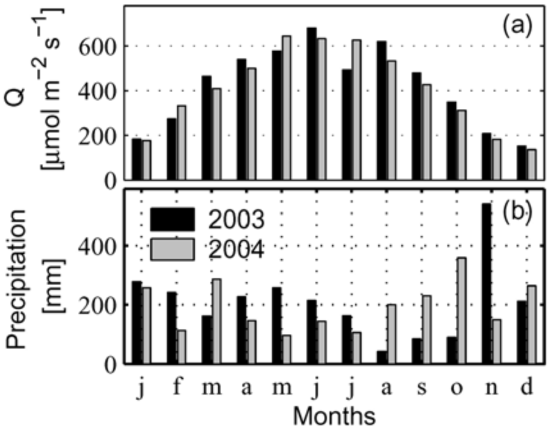

Figure 5.1 (a) Monthly Q, averaged for the daytime and (b) monthly precipitation during 2003 and 2004.

Daily air and soil temperatures (Figures 5.2a and 5.2b) confirmed a very mild climate with little variation throughout the year. The annual average air temperature was 10.51 (2003) and 10.40 ºC (2004). T_a average during the May to September period was 13.60 (2003) and 13.59 ºC (2004); in November-February it was 7.40 (2003) and 7.84 ºC (2004). The daily soil temperature at 20 cm depth was between 5 and 18 ºC. The WT (Figure 5.2c) remained close to the surface throughout the year. The range of WT was from 2 cm above the *LL* to about 15 cm below the *LL* surface.

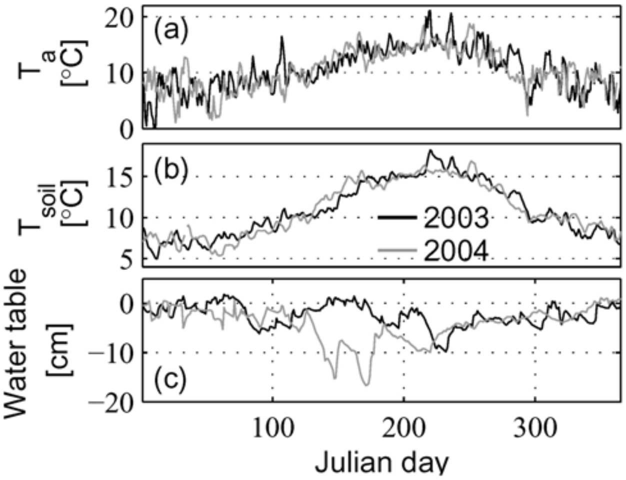

Figure 5.2. (a) Daily mean air temperature; (b) daily soil temperature at 20cm depth; (c) Water table variation during 2003 and 2004.

The monthly CO_2 flux (Figure 5.3) for both 2003 and 2004 showed a net uptake over the five months, May to September, and a net respiration for the four months, November to February. In both years, March, April and October showed no clear net flux, either uptake or respiration. In both 2003 and 2004, July was the month with the highest CO_2 uptake: -20 and -28 g C m^{-2}, respectively. High and similar uptakes of CO_2 for the two years were also noted in June (about -18 g C m^{-2}) and August, with -16 and -19 g C m^{-2} in 2003 and 2004.

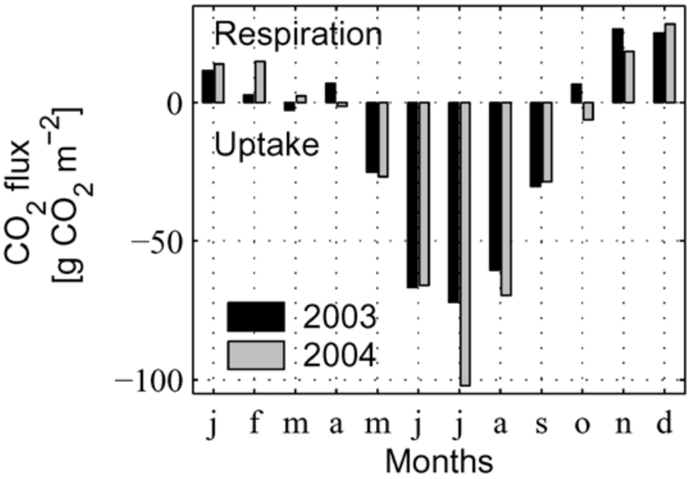

Figure 5.3. Monthly CO_2 flux during 2003 and 2004.

The cumulative CO_2 flux (Figure 5.4) showed a net uptake in 2003 of -49 g C m^{-2} yr^{-1} and in 2004 of -61 g C m^{-2} yr^{-1}. The error in the energy balance closure provided an estimate of the systematic error. The approach of *Aurela et al.* [2002] was used to estimate the random component of the error, which was much lower. The combined error estimate was approximately 35 and 30% for 2003 and 2004 respectively. The inflections points (up arrows, Figure 5.4) mark the beginning of the ecosystem net CO_2 uptake period that occurred at the end of April in both years. The end of the net CO_2 uptake period (down arrows, Figure 5.4) was late September for 2003 and mid October for 2004. The annual net CO_2 uptake was close to what was estimated for a Scottish blanket bog (-41 g C m^{-2} yr^{-1} (Beverland et al., 1996)) and measured over four consecutive years in a Canadian boreal raised bog (-76, -69, -68 and -10 g C m^{-2} y^{-1} (Lafleur et al., 2003)). A higher annual CO_2 balance was estimated for a boreal fen in Russia (-88 g C m^{-2} y^{-1} (Friborg et al., 2003)) while generally lower values were measured in six consecutive years in a subarctic fen in Finland (-4, -21, -8, -6, -37 and -53 g C m^{-2} y^{-1} (Aurela et al., 2004)).

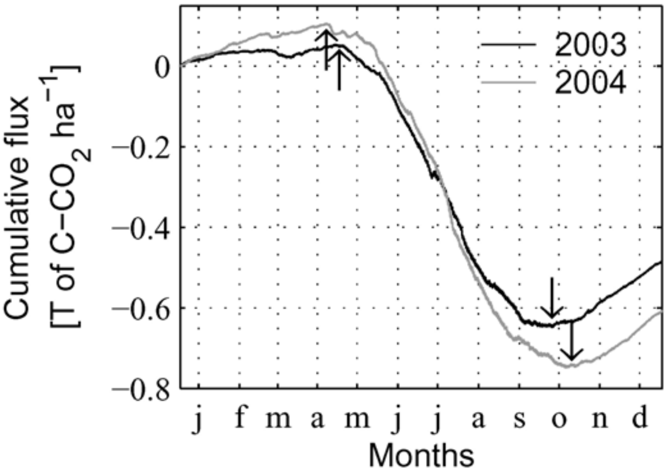

Figure 5.4. Cumulative CO_2 flux during 2003 and 2004.

5.6 Discussion

Previous CO_2 flux studies in northern peatlands have been performed in boreal, sub-arctic or arctic regions. All these regions experience extreme weather conditions, with a short growing season and a long winter with frozen soil and snow cover. In contrast the temperate climate of Ireland varies little throughout the year and is characterized by a long growing season and a mild winter with only rare snowfall, and typically without any occurrence of frozen soil. The present work is the first EC study in an Atlantic blanket bog, ecosystem characterized by a different climate to previous studies of peatlands in northern regions.

Two years of EC CO_2 flux measurements, while too short for definitive conclusions about interannual variation, are long enough to quantify the seasonal variation of the CO_2 source/sink status of this ecosystem. The C budget of a peatland has three main components: CO_2 and CH_4 fluxes and DOC losses in streams. Our study does not report on CH_4 or DOC. However the CO_2 flux is expected to be the largest component of the C cycle (Moore et al., 1998). According to this study, the CO_2 flux pattern of Atlantic blanket bog in Ireland is, in terms of the annual balance, lower than boreal fen (Friborg et al., 2003), higher than subarctic fen (Aurela et al., 2004) and similar to boreal raised bog (Lafleur et al., 2003). As the water table is persistently higher in the blanket bog, decomposition was expected to be lower and therefore CO_2 uptake higher than in boreal raised bogs (Lafleur et al., 2003). However other processes are likely to reduce the impact of the water table height in terms of CO_2 uptake in the blanket bog. These are: 1) lower LAI and lower moss cover in the blanket bog, and therefore lower gross ecosystem production and CO_2 uptake compared to the boreal raised bog; 2) higher litter decomposition rate of the plant species in the blanket bog (Aerts et al., 1999), and therefore lower CO_2 uptake than in the boreal raised bog.

Although Glencar has a mild maritime climate, the blanket bog is a net sink for CO_2 for only five months of each year, even if some daily net photosynthesis has been measured also during the winter (data not shown).

Over the two years of continuous measurement, the Glencar blanket bog showed an average net CO_2 uptake of -55 g C m^{-2} y^{-1}, which is ~ 20% of an average annual

CO_2 flux of –277 g C m^{-2} yr^{-1} in a nearby fertilized grassland for the same two years (Lawton et al., 2006). If we extrapolate our estimate of the CO_2 fluxes at the Glencar ecosystem to the entire 240,000 ha of Irish blanket bogs, with the rough assumption that all pristine and disturbed blanket bogs have comparable CO_2 fluxes, we can estimate the annual CO_2 uptake for this ecosystem to be of the order of 0.1 Mt C yr^{-1} in Ireland.

Climate change scenarios for Ireland predict a warmer climate with a decrease in precipitation in summer and an increase in winter (McGrath et al., 2005). The effects of this climate change on CO_2 fluxes is unknown, as a change in temperature and in precipitation will affect in different ways both components of the CO_2 flux, respiration and photosynthesis. Along with further EC measurements, we intend to extend this work to modeling the CO_2 flux and so evaluate some future climate change scenarios and resolve the synergies of the predicted climate change on the ecosystem CO_2 balance.

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Water balance, evaporation and energy fluxes in an Atlantic blanket bog in South-western Ireland

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6.1 Abstract

Water and energy fluxes control the development of northern peatlands and influence their carbon budget. Atlantic blanket bogs are peatlands that occur in maritime regions where precipitation is much greater than evapotranspiration. In this paper four years (October 2002 to September 2006) of evapotranspiration and energy fluxes were examined in the context of the predicted climate change for South-western Ireland. The full water balance (precipitation, evapotranspiration, stream flow and water table change) for the hydrological year 2002/2003 was also analysed.

The Atlantic blanket bog ecosystem was found to have a higher Bowen ratio and lower evapotranspiration than other peatland types, despite having higher precipitation and water table. Evapotranspiration seems to be limited by the low occurrence of vascular plants and mosses (essential for transpiration), rather than by the low vapour pressure deficit and cool summer air temperature. A comparison between the four years suggests that the predicted climate change will probably increase winter evapotranspiration and lead to an earlier start of the growing season. The expected decrease in summer precipitation will probably not affect the major evapotranspiration patterns of the bog. However, if the frequency of summer rain events should diminish, the moss component of these ecosystems may become water-stressed, ultimately leading to lower evapotranspiration.

6.2 Introduction

The development of peatlands is closely related to regional climate controls on precipitation and evaporation and is thus strictly controlled by the water and energy fluxes. The water balance in peatlands is connected to carbon sequestration (Shurpali et al., 1995; Lafleur et al., 1997; Lafleur et al., 2003), as the depth of the water table determines the soil temperature, the depth of the peat layer available for aerobic respiration and the water available for plants, which in turn influences their photosynthesis ability. As the water balance is predicted to be affected by climate change (Roulet et al., 1992), a better understanding of the water and energy fluxes in peatlands is necessary if we are to predict the effect of climate change on these fragile ecosystems.

Many studies in recent years have focused on the energy balance and evaporation process in different peatland types (Kurbatova et al., 2002; Shimoyama et al., 2003; Shimoyama et al., 2004). Available energy in peatlands is generally consumed more for latent than sensible heat flux (Rouse, 2000; Valentini et al., 2000; Shimoyama et al., 2003). Evapotranspiration (ET) was found to be well correlated to but considerably lower than potential ET (Lafleur et al., 2005; Humphreys et al., 2006). Nevertheless ET has been observed to be relatively independent of water table depth (Lafleur et al., 2005; Humphreys et al., 2006) and similar in years with different precipitation (Kurbatova et al., 2002). The mechanisms of ET vary in different peatland types, being strongly controlled by surface conductance in peatlands with high vascular plant cover (Humphreys et al., 2006), and by available radiation in moss-dominated peatlands (Kellner, 2001; Kurbatova et al., 2002; Shimoyama et al., 2003).

Blanket bogs are ombrotrophic peatland ecosystems whose development is mostly independent of basin or topographical features where water can collect. They are so called because they blanket the landscape (Tansley, 1965) on slopes with gradients up to 20-25° (Clymo, 1983; Tallis, 1998). Globally, blanket bogs are rare ecosystems, accounting for ca. 3% of the world peatland area (Foss et al., 2001), as their distribution is restricted to maritime regions. The development of blanket bogs requires cool summers and winter mean temperatures > 4 °C (Doyle & Moore, 1978) and high precipitation (> 1250 mm yr^{-1}), with more than 225 rainy days (Hammond, 1981; Taylor, 1983) or 160 wet days (i.e. > 1 mm day^{-1}) per year

(Tallis, 1998). Furthermore precipitation exceeds ET by at least 200 mm over the growing season period (April-September) (Tallis, 1998). The vegetation cover of blanket bogs is modest in terms of both vascular and bryophyte plants (Sottocornola et al., submitted to Journal of Ecology).

Price (1992) found that the hydrology of a blanket bog in Newfoundland was dominated by stream discharge. Even if higher ET was measured during clear weather, due to higher available radiation, in rainy and foggy conditions ET was closer to its equilibrium rate (Price, 1991), suggesting a strong link between ET and soil surface wetness in blanket bogs. The CO_2 annual balance in Atlantic blanket bogs was reported to be similar to boreal raised bogs, although both gross ecosystem production and respiration were lower (Sottocornola & Kiely, 2005; Roulet et al., 2007). To better understand the functioning of Atlantic blanket bogs it is therefore important to extend the comparison of water and energy fluxes with boreal raised bogs and other peatland types.

Climate change in Ireland is predicted to cause an increase in temperature between 1.25 and 1.5 °C, a decrease in summer precipitation and an increase in winter precipitation for the 2021-2060 period (McGrath et al., 2005), a trend that has been detected in the west of the country from the mid-1970s (Hoppe & Kiely, 1999; Kiely, 1999). The only studies of hydrological and energy processes performed in a blanket bog, to the authors knowledge, were done in the early nineties in Newfoundland (Price, 1991; Price, 1992). Moreover, studies about the annual water balance in peatlands and about multi-year comparison of energy and water processes (Lafleur et al., 2005; Admiral et al., 2006) are still relatively rare.

In this paper we report on one year of water balance, and four years of evapotranspiration and energy fluxes. The goals of this paper are 1) to describe the water and energy fluxes in an Atlantic blanket bog by comparison with other peatland types; 2) to identify the mechanisms of evapotranspiration and 3) to analyse the interannual variations in the context of the predicted climate change. Data was analysed based on the hydrological year, October 1 to September 30.

6.3 Site Description

The experimental site is an Atlantic blanket bog located near Glencar, County Kerry, in Southwest Ireland (Latitude: 51° 55' N, Longitude: 9° 55' W) at an approximate elevation of 150 m above sea level. The present study was confined to the pristine central part, of about 220 ha, of the peatland. This area is drained by a stream, whose catchment boundaries are located inside the bog on the West and East and defined by small country roads on the North and South (Figure 6.1). The catchment of the peatland stream is 95 ha, of which 88 % is on the pristine bog and 12 % is on a hill slope covered by patches of grassland and peaty soils (Figure 6.1). The characteristic feature of the bog is a spatially heterogeneous surface, with a mosaic of microforms, which differ in relative altitude, plant composition and water table depth. We divided these microforms into four classes based on their relative elevation: hummocks, high lawns, low lawns and hollows (Laine et al., 2006). The elevation difference between the highest and lowest microform is typically 20 to 40 cm. Hollows are depressions covered by standing water for most of the year. The distribution of microform type inside the peatland was estimated as 9 % hummocks, 77 % high lawns, 9 % low lawns and 3 % hollows (Sottocornola et al., submitted to Journal of Ecology). Vascular plants cover about 30 % of the bog surface, the most common species being *Molinia caerulea* (purple moor-grass), *Calluna vulgaris* (common heather), *Erica tetralix* (cross-leaved heath), *Narthecium ossifragum* (bog asphodel), *Rhynchospora alba* (white beak-sedge), *Eriophorum angustifolium* (common cotton grass), *Schoenus nigricans* (black-top sedge) and *Menyanthes trifoliata* (buckbean) (Sottocornola et al., submitted to Journal of Ecology). The bryophyte component is not widespread (about 25 % of the bog surface) and the principal species include a brown moss, *Racomitrium lanuginosum* (wolly-hair moss), and *Sphagnum* mosses (bog mosses) (Sottocornola et al., submitted to Journal of Ecology), occurring in the peatland with similar abundance. The peat depth is > 2 m in most parts of the peatland.

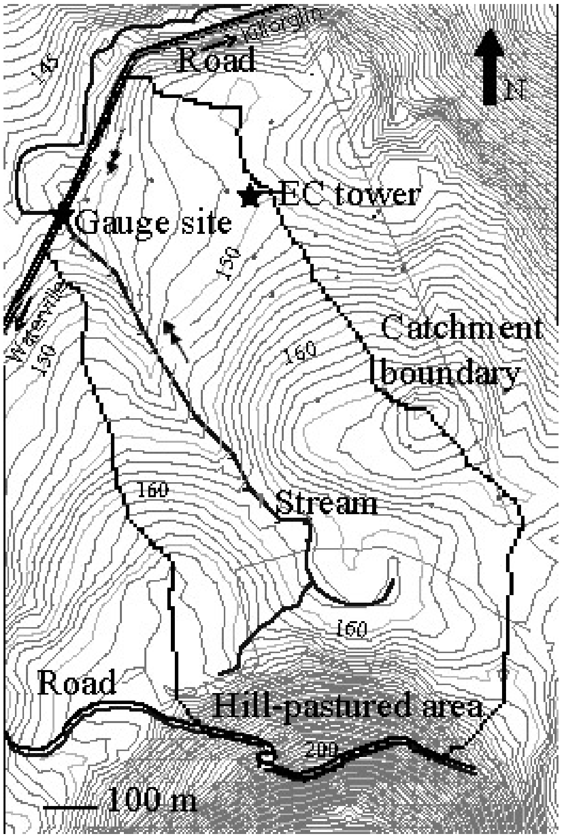

Figure 6.1. Map of the study site, with catchment borders. Stream catchment area = 95 ha. (EC = eddy-covariance)

6.4 Methods

6.4.1 Stream flow measurements

Stream flow was measured at the outfall of the stream draining the pristine central part of the peatland. The stream stage was continuously recorded at a frequency of 30 minutes using a Thalimedes water level recorder (OTT, Germany), during the 12-month period, 10th October 2003 to 9th October 2004. The discharge was manually measured on 17 occasions with a current metre (C 20, OTT, Germany) at a rectangular shaped cross section of the stream. The rating curve is shown in Figure 6.2, with a best equation of the form:

$$Q = a * (h - c)^b \tag{6.1}$$

where Q is the stream discharge, h is the stream stage, a, b and c are parameters. The stream stage records were converted to continuous discharge data using equation (1). The R^2 of the relationship was 0.95.

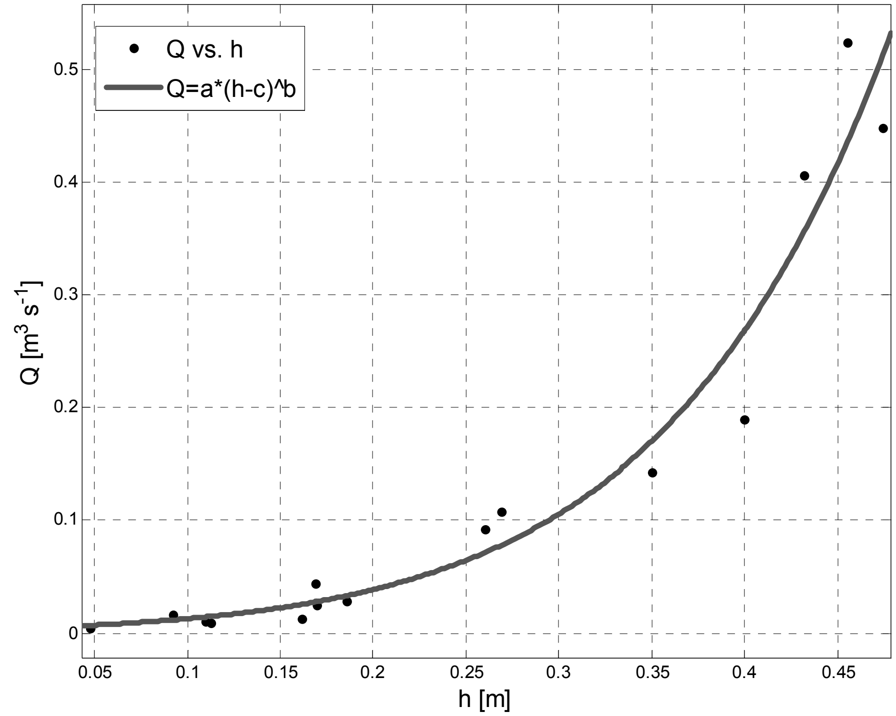

Figure 6.2. Rating curve to transform stream stage height in stream discharge. The R^2 of the relationship is 0.95.

6.4.2 Meteorological measurements

Meteorological variables were measured in the centre of the bog at the EC/meteorological tower (Figure 6.1). The meteorological equipment included a net radiometer (CNR 1, Kipp & Zonen, the Netherlands) and a sensor for QPAR, photosynthetically active radiation (PAR Lite, Kipp & Zonen, the Netherlands). Wind speed was recorded with 3-D (Model 81000, R.M. Young Company, USA) and 2-D sonic anemometers (WindSonic, Gill, UK). Air temperature (T_{air}) and relative humidity were measured at 2 m height with a shielded probe (HMP45C, Vaisala, Finland), while atmospheric pressure was recorded with a barometer (PTB101B, Vaisala, Finland). Soil temperature was measured with a probe (107, Campbell Scientific, UK) at 5 cm (since the 11th March 2005) and 20 cm below the high lawn vegetation, while soil water content was recorded with a water content reflectometer (CS615, Campbell Scientific, UK). Ground heat flux (G) was measured with two plates (HFP01, Hukseflux Thermal Sensors, the Netherlands), buried at 5 cm below the soil surface and corrected for storage heat (Brutsaert, 1982; Campbell & Norman, 1998). Precipitation was measured with two tipping bucket rain gauges (an ARG100, Environmental Measurements Ltd., UK and an Obsermet OMC-200, Observator BV, The Netherlands). The water table (WT) depth was recorded under low lawn vegetation with a pressure transducer (PCDR1830, Campbell Scientific, UK) placed inside a metal well pierced all along its height. A malfunction of the WT transducer between November 2002 and May 2004 was corrected with interpolation from manual measurements (Laine et al., 2007). Signals from all the meteorological sensors were monitored every minute and averaged over a 30-minute period in a CR23X data logger (Campbell Scientific, UK).

6.4.3 Eddy covariance measurements

Evapotranspiration was calculated from the transformation of latent heat flux (LE). Latent and sensible heat fluxes were estimated using the eddy covariance (EC) technique. The EC system was located in the same place as the meteorological station (see Figure 6.1), in a flat area of the pristine part of the bog. The EC system consisted of a 3-D sonic anemometer (Model 81000, R.M. Young Company, USA) and an open-path infrared gas analyser (LI-7500, LI-COR, USA) mounted 3 m above high lawn vegetation. Data were recorded at 10 Hz and fluxes were Reynolds-averaged every half-hour. The 30-minute averaged LE was measured via the eddy covariance technique as:

$$LE \cong L_v \overline{w' \rho_v '} \tag{6.2}$$

where L_v (kJ kg^{-1}) is the latent heat of vaporization, w' is the vertical wind velocity fluctuations (m s^{-1}) and ρ_v' is the water vapour density fluctuation (g m^{-3}). The 30-minute averaged sensible heat flux (H) was also estimated via the EC technique as:

$$H \cong \rho_a c_p \overline{w'T'} \tag{6.3}$$

where ρ_a is the air density (kg m^{-3}), c_p is the specific heat capacity of moist air (J kg^{-1} $°C^{-1}$) and T' the air temperature fluctuations (°C).

10 Hz data were checked online for quality and measurements over or below predetermined realistic threshold values were discarded. Post-field data processing included a double rotation on raw EC flux data, so that the mean horizontal wind speed was rotated into the mean wind direction and the mean vertical wind velocity was set to zero, by correcting the fluxes for the averaged 30-minute angle between the horizontal and vertical axes. The LE was corrected for variations in air density (Webb et al., 1980), while H was corrected for air moisture (Shotanus et al., 1983). Filters were then established to discard bad flux estimates. Half-hour mean flux data were rejected if: 1) less than 95 % of the 10 Hz data passed the online 10 Hz filters; or if 2) the estimate of the vertical angle gave unrealistic outputs (typically in low wind speed conditions); or if 3) the product between net radiation (R_n) and H gave a negative output; or if 4) less than 67 % of the flux footprint length was estimate to have originated outside the pristine part of the bog (see Laine et al., 2006 for details); or if 5) the fluxes were measured during rainy periods or up to one hour after rain, because the open-path gas analyser is known to be unreliable in wet conditions. Finally, LE values were rejected if they were lower than –30 and higher than 280 W m^{-2}, while winter LE were filtered for predetermined realistic threshold values for each month.

Between the 25th May and 4th June 2003 no data were logged due to an electricity outage. The missing meteorological data were replaced with the last 5 good days of data before the outage and the first 5 days of good data after the outage except for precipitation. Precipitation data were obtained from a comparison with the records of the nearby Met Eirann synoptic weather station at Valentia (30 km west of the site, 51° 56' N, 10° 14' W). Shorter meteorological gaps were replaced either with interpolation (all data up to 4 hours gap, except radiation data) or with average of previous and following 7 days (radiation data, and all data for gaps longer than 4 hours). Missing short-wave incoming radiation data were modelled based on a relationship with PAR (R^2=0.99), while missing R_n values were replaced by a relationship with QPAR (R^2=0.94). The soil heat flux suffered a break between the 19th December 2004 and the 9th March 2005. The missing data were replaced by the average of the other three years for the same period. The EC system suffered three breaks, between the 21st May and 26th June 2003, between 21st January and 2nd February 2005 and between the 16th and 23rd March 2005.

After post-processing and filtering, approximately 51 % of LE data in the hydrological year 2002/03 (56 % of daytime LE, thus when incoming short-wave radiation was ≥ 10 W m^{-2} s^{-1}), 49 % in 2003/04 (58 % of daytime LE), 38 % in 2004/05 (41 % of daytime LE) and 49 % in 2005/06 (55 % of daytime LE) was considered good and suitable for further analysis. Most of rejected flux data was from the winter time.

The gaps in the LE time series were filled with a linear regression equation between daytime 30-minute LE derived from potential evaporation (PET) and 30-minute daytime measured LE for each year, established using the Curve Fitting Tool of MATLAB 7.0.1 (MathWorks Inc., USA). This relationship had an R^2 of 0.47, 0.55, 0.52 and 0.58 in 2002/03, 2003/04, 2004/05 and 2005/06, respectively. The Penman-Monteith equation, with surface resistance set to zero, was used as an estimate of PET:

$$PET = \frac{\Delta * (R_n - G) + \rho_a * c_p * (\frac{VPD}{r_a})}{L_v * (\Delta + \gamma)} \tag{6.4}$$

where Δ is the slope of the of the relationship between saturation vapour pressure and temperature (kPa $°C^{-1}$), VPD is the vapour pressure deficit (kPa), r_a is the atmospheric resistance (s m^{-1}) and γ is the psychrometric constant (kPa $°C^{-1}$). Missing H were replaced with solving the energy balance equation for H:

$$H = (R_n - G) - LE \tag{6.5}$$

The Bowen ratio (β) was calculated as H/LE. The equilibrium evapotranspiration (ET_{eq}) was estimated using the Priestly-Taylor equation (Priestley & Taylor, 1972), and α was defined as ET/ET_{eq}. The surface conductance (g_s) is the inverse of the surface resistance and was estimated by a rearrangement of the Penman-Monteith equation. One-sided leaf area index (LAI) was measured in two hydrological years, 2004/05 and 2005/06 using a PAR/LAI Ceptometer (LP-80 AccuPAR, Decagon devices, Inc., USA).

6.5 Results

6.5.1 Water budget

All components of the water budget were continuously measured between the 10th October 2003 and the 9th October 2004, which coincides approximately with the hydrological year. The annual precipitation was 2485 mm; the total stream discharge was 1852 mm; and the actual evapotranspiration was 404 mm (Figure 6.3). The water table depth on the 9th October 2004 was 5 mm above that on the 10th October 2003 (Appendix 1). The discharge appeared flashy and closely followed the precipitation pattern until the beginning of April when it responded less promptly to rainfall due to the increased importance of ET.

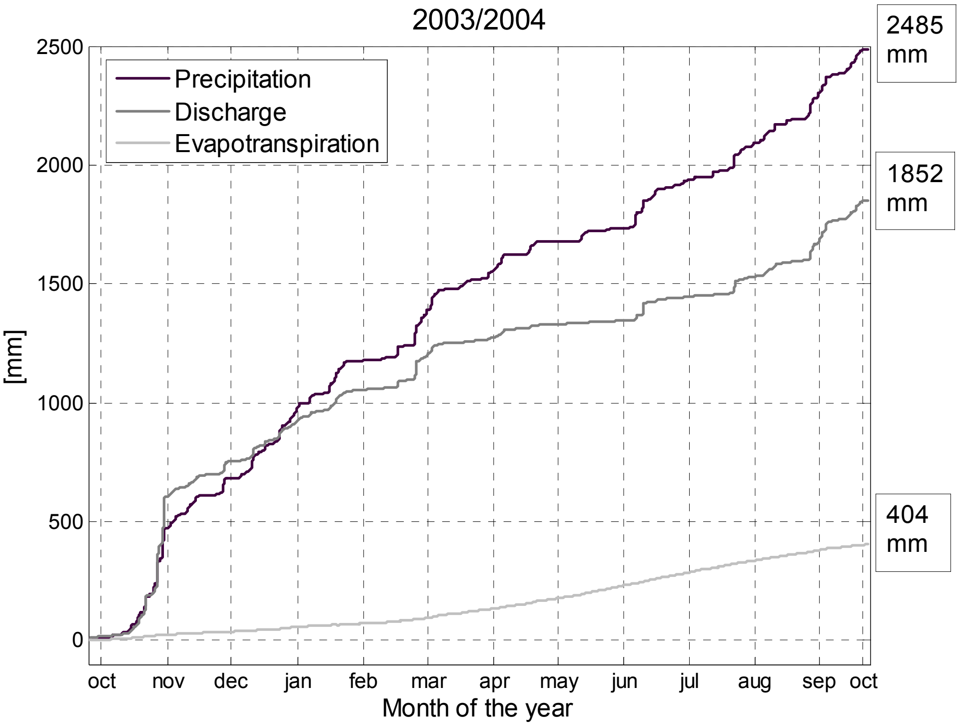

Figure 6.3. Cumulative sums of the main components of the annual water balance measured between the 10th October 2003 and the 9th October 2004.

Precipitation and ET in the hydrological years between 2002 and 2006 were similar to those measured for the annual water balance of 2003/04. Precipitation ranged between 2428 and 2724 mm, while ET varied between 357 and 406 mm (Figure 6.4, Table 1).

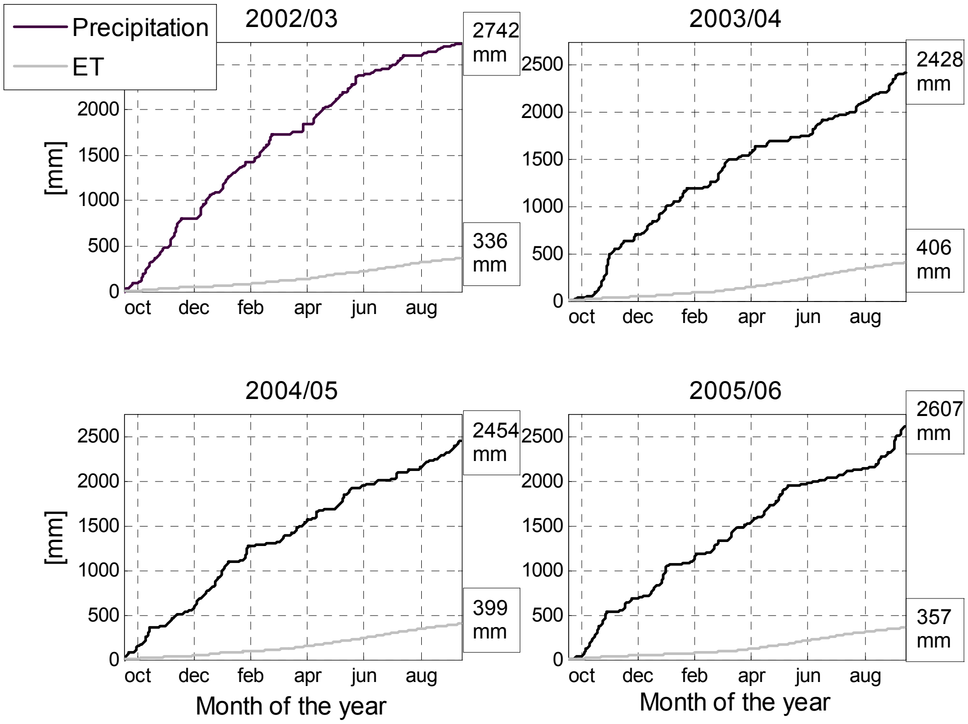

Figure 6.4. Cumulative sums of precipitation and ET between the 1st October and the 30th September of each year between 2002 and 2006.

Table 6.1. Annual and growing season (April-September) sums of precipitation, evapotranspiration, ET/ precipitation at the Glencar Atlantic blanket bog. T_{air}, R_n and VPD are averages of daytime data.

	2002/03 (Apr-Sept)	2003/04 (Apr-Sept)	2004/05 (Apr-Sept)	2005/06 (Apr-Sept)	All years (Apr-Sept)
Precipitation (mm)	2742 (988)	2428 (925)	2454 (1040)	2607 (1143)	2558 (1024)
ET (mm)	366 (240)	406 (280)	399 (271)	357 (257)	382 (262)
ET /Precipitation	0.13 (0.24)	0.17 (0.30)	0.16 (0.26)	0.14 (0.22)	0.15 (0.26)
Daytime T_{air} (°C)	11.49 (14.02)	11.26 (13.70)	11.48 (14.00)	11.50 (14.31)	11.43 (14.01)
Daytime R_n (W m^{-2})	114.60 (167.32)	123.14 (179.87)	123.66 (178.33)	126.17 (190.68)	121.89 (179.05)
Daytime VPD (kPa)	0.29 (0.35)	0.29 (0.33)	0.26 (0.31)	0.28 (0.35)	0.28 (0.34)

6.5.2 Dormant season (October to March)

Daily ET between October and March varied considerably from day to day. The monthly mean ET ranged between a minimum of 0.4 mm in December 2005 and a maximum of 1.1 mm day^{-1} in March 2004 (Figure 6.4). In winter, ET appeared to closely follow the daytime temperature, often exceeding 1.5 mm day^{-1} during days warmer than 10 °C. In most years, December had the lowest monthly mean daily ET (about 0.4 mm day^{-1}). The 2004/05 winter was different from the other winters, with the lowest monthly ET occurring in November, while December had similar ET as February, and January had a higher ET than March, due to very mild daytime temperatures.

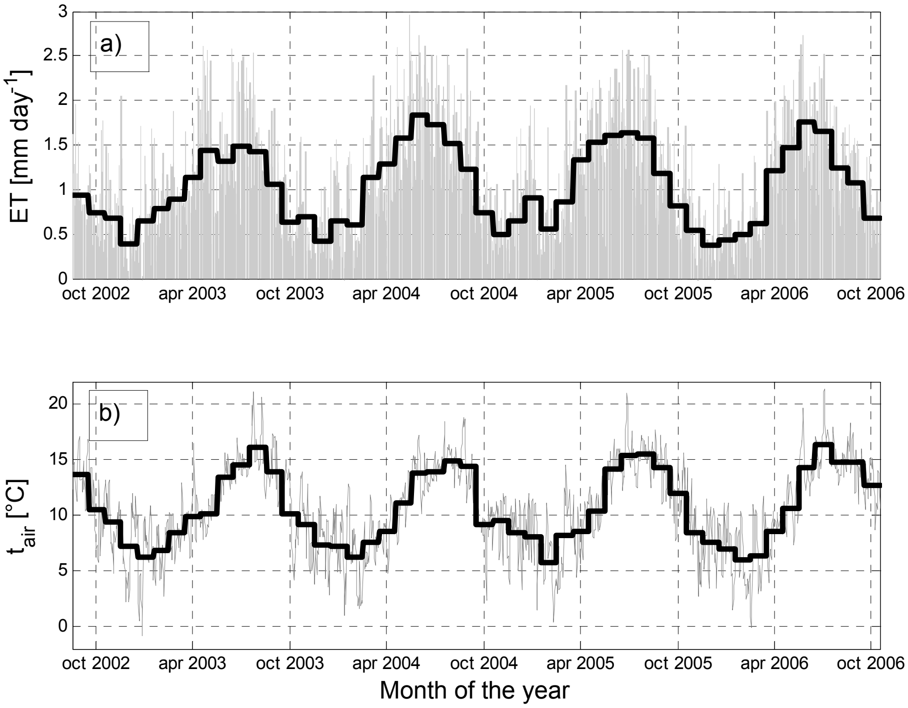

Figure 6.5. a) Daily evapotranspiration (bars) and superimposed monthly mean ET (heavy black line) for the period 1st September 2002 to 31st October 2006. b) Daily T_{air} (grey line) and superimposed monthly mean T_{air} for the same period.

6.5.3 Growing season (April to September)

The one-sided Leaf Area Index in the study site varied between a minimum of 0.2 $m^2 m^{-2}$ in winter and a maximum of 0.6 $m^2 m^{-2}$ in mid-August (Figure 6.6). The growing season began at a different time in the two years of LAI measurements. In spring 2005 the vascular plants started to leaf-out at the beginning of May, while in 2006 only in June. The LAI in 2006 was lower than in 2005 for the entire spring, but eventually reached similar values during the summer. The senescence started in the two years at around the same time, in September.

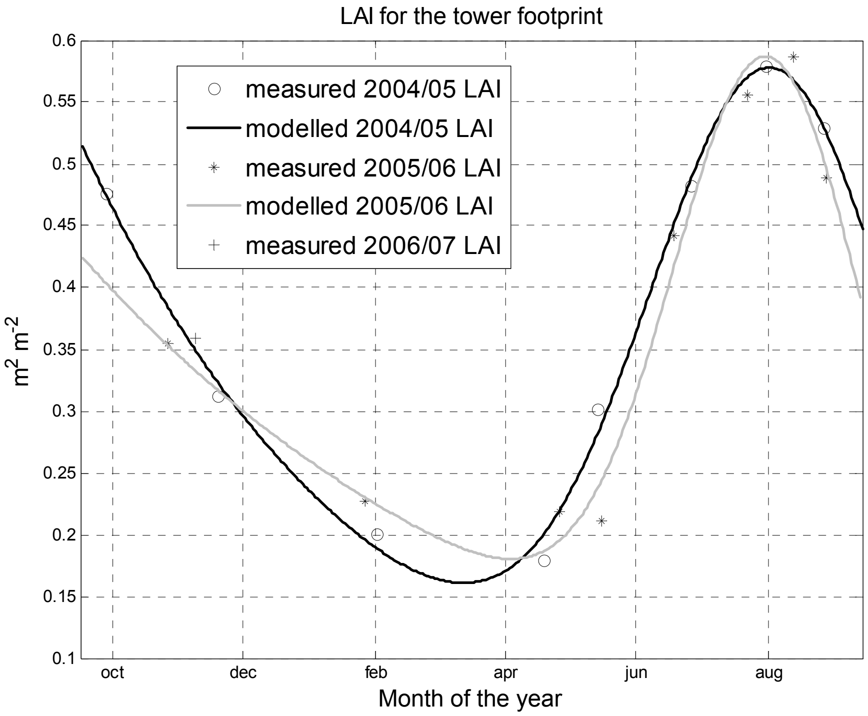

Figure 6.6. LAI measurements and curve fits for the hydrological years 2004/05 and 2005/06. Also shown is a measurement taken at the end of November 2006.

During the growing season, precipitation was very abundant and ranged between 925 and 1143 mm, being on average 40 % of total annual precipitation (Table 1). Rainfall events occurred very frequently, with a maximum of 13 days without precipitation, and only three periods, over the four studied years, without rain for longer than eight days (Figure 6.7). The water table consequently remained high during the summer, dropping below 15 cm under low lawns only in June 2004 and in July 2006.

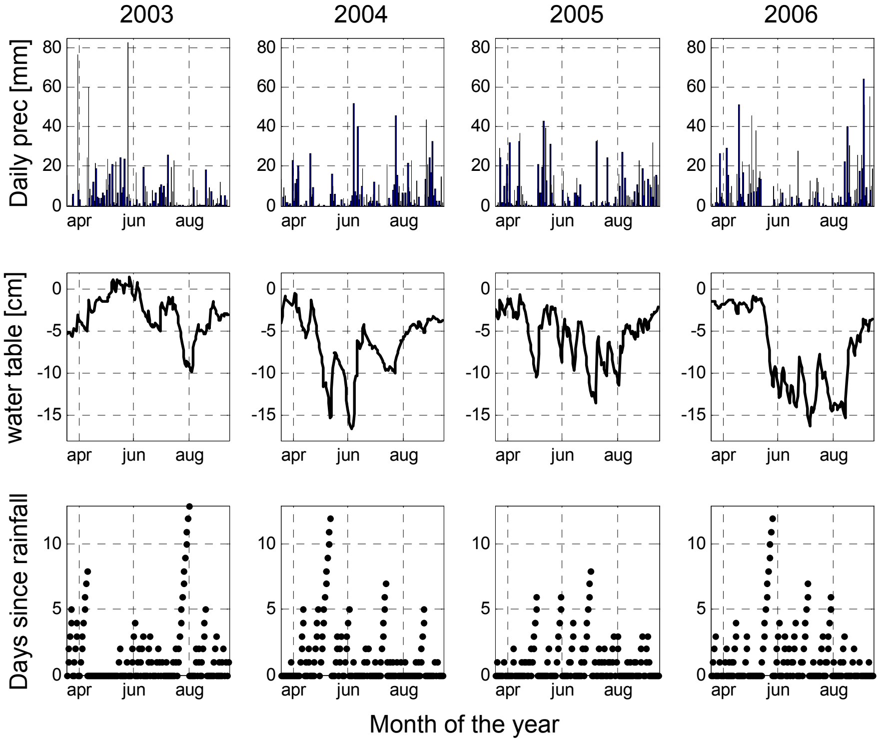

Figure 6.7. Daily precipitation, water table depth and number of days since previous rainfall during the growing season (April-September) in 2003, 2004, 2005 and 2006.

The ET ranged between 240 and 280 mm during the six-month growing season, accounting for about 69 % of the total annual ET (Table 1). The ET/precipitation ratio was low during the growing season and varied between 0.22 and 0.30, in the 4 studied years. The monthly mean daily ET was greatest in June and July, ranging between 1.3 and 1.8 mm day^{-1} with the highest daily ET varying between 2.5 and 3 mm day^{-1} (Figure 6.5).

The spring in 2003 and 2004 experienced very different weather conditions (Figure 6.7). May and early June were very wet in 2003 and dry in 2004 so that the water table was high in spring 2003 and low in spring 2004. Low radiation and cool temperatures in the spring of 2003 (Figure 6.8) caused the lowest ET for that period in the four years (0.8 mm day^{-1}), while higher radiation and higher temperatures in spring 2004 resulted in high ET (1.3-2 mm day^{-1}). Contrasting precipitation patterns occurred in the growing seasons in 2005 and 2006. Precipitation in 2005 was regular and frequent with a maximum of 8 days without rainfall, which generally kept the summer water table higher than 10 cm below the peat surface (Figure 6.7). The 2006 spring was rainy and cool till the end of May, when a 12 days period of dry weather, high temperature and radiation lead to a drop in water table deeper than 10 cm below the soil surface where it remained until the end of August, except for few individual rain events (Figure 6.7). As a result of two periods with high VPD, T_{air} and R_n, the highest daily ET were recorded in 2006. However, the ET during the growing season was higher in 2005 (271 mm) than 2006 (257 mm) (Figure 6.8), despite lower daytime T_{air}, R_n and VPD in 2005 (Table 1).

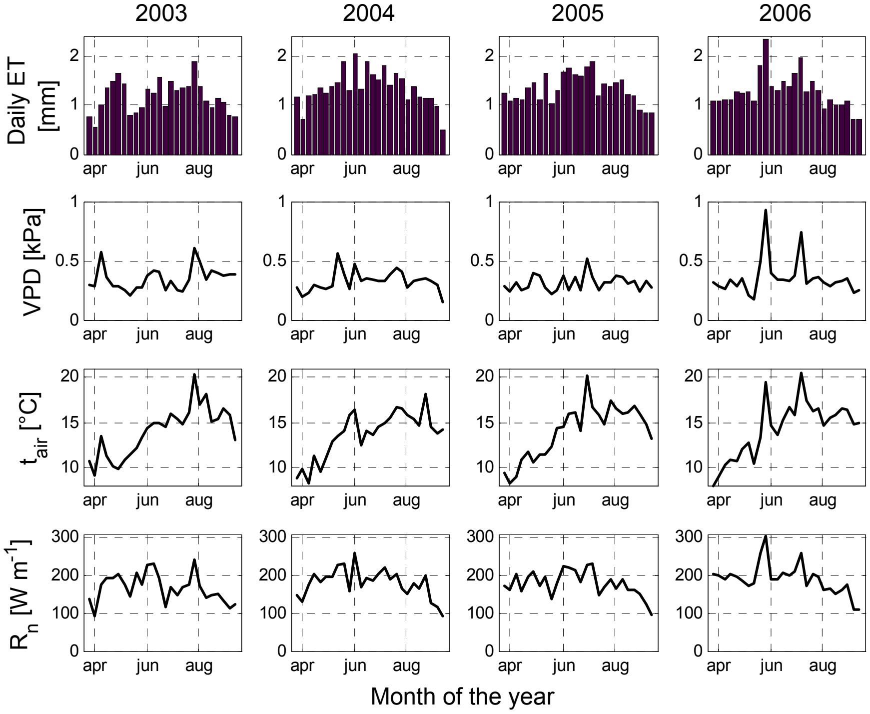

Figure 6.8. Daily (averaged over 7 days) ET and daily means (averaged over 7 days) of VPD, T_{air} and R_n during the growing season (April-September) in 2003, 2004, 2005 and 2006.

6.5.4 Evapotranspiration mechanism

Evapotranspiration had an interannual variability, ranging from a low of 357 mm in 2005/06 to a high of 406 mm in 2003/04. In Figure 6.9a we show the daily ET relative to the depth of the water table below the surface of the low lawn vegetation. This suggests no clear dependence of ET on water table depth. Besides we note in Figure 6.9b that the mean ratio of daily ET/PET is almost constant at ca. 0.45 for all water table depths.

a)

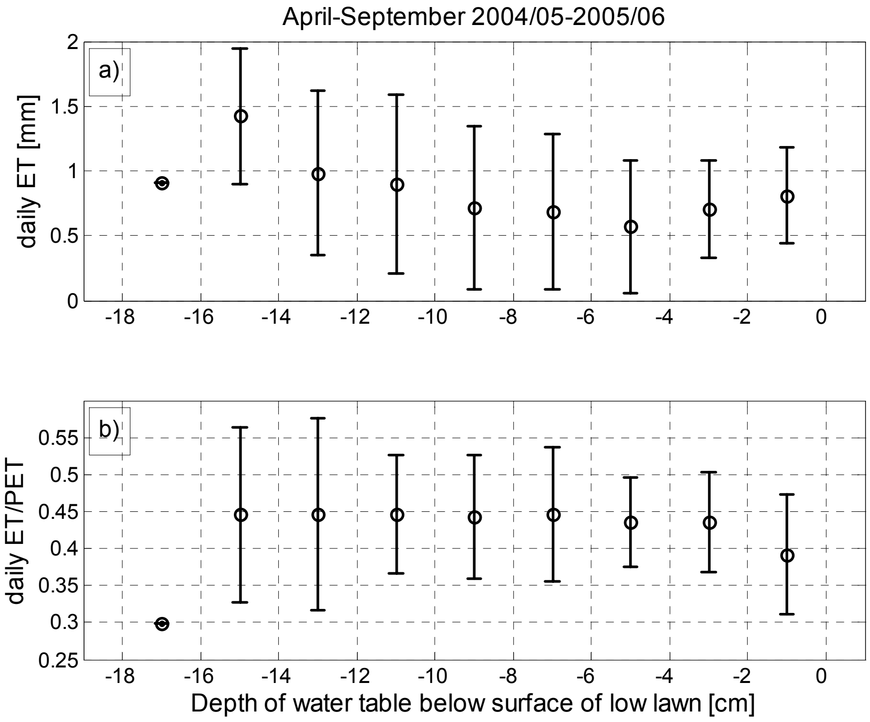

Figure 6.9. a) Daily evapotranspiration plotted for 2 cm water table classes for the 2005 and 2006 growing season periods together. Points represent mean values, while bars represent standard deviations. b) as a), except ratio of daily ET to potential ET.

The daily ET exhibited a very close relationship with daily potential ET in all four studied years (Figure 6.10), with correlation coefficients between 0.50 and 0.71. The measured ET was between 0.36 and 0.49 of PET, being highest in 2004/05 and lowest in 2005/06.

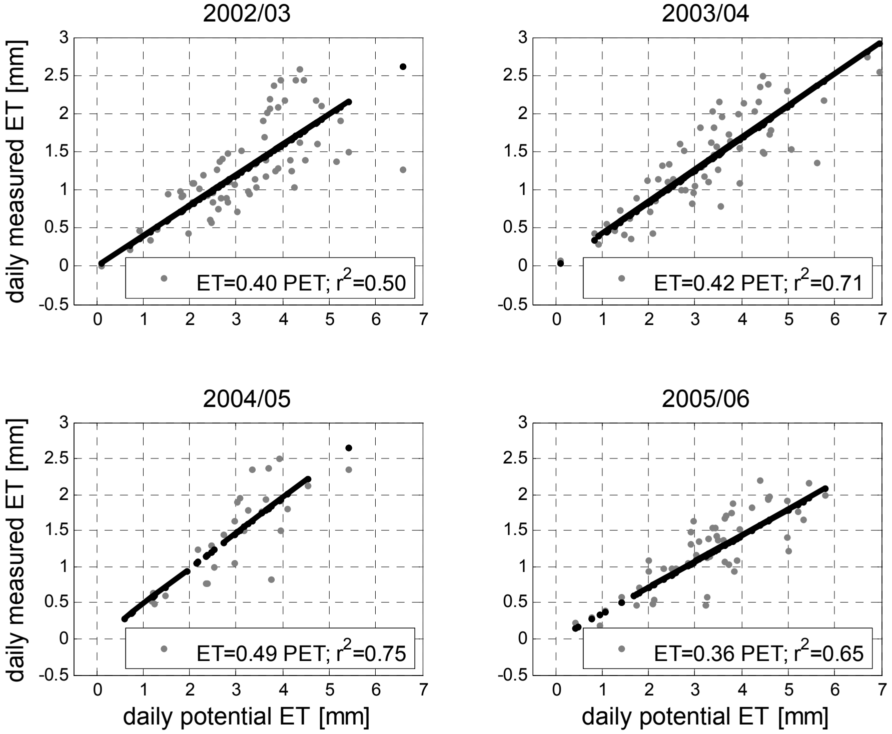

Figure 6.10. Relationship between daily ET and PET in the four studied hydrological years. Only daily values when > 75 % of LE data were good are shown.

The latent heat flux related well with net radiation (R_n) (Figure 6.11). Between 71 and 80 % of the variation in LE during the growing season was explained by R_n. The amount of R_n used for LE was between 0.24 and 0.30, being highest in the growing season in 2004/05 and lowest in 2005/06. We consider the offset in the equations of Figure 6.11 to be due to the advective component of ET.

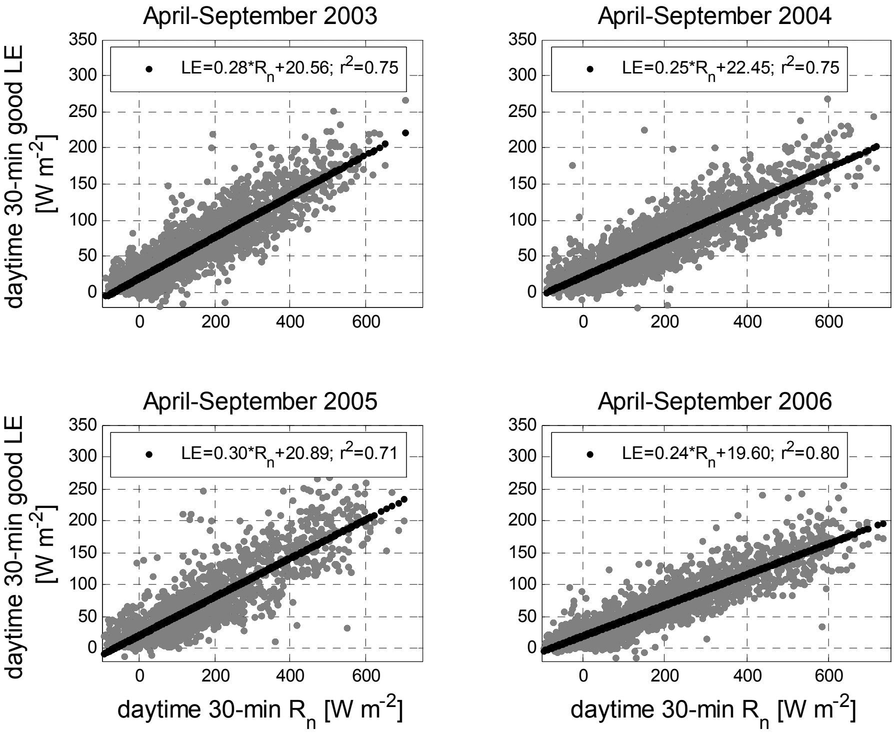

Figure 6.11. Relationship between 30-minute good LE and R_n in the four studied growing seasons. We considered the offset in each of these four figures to be due to the advection component of ET.

LE was well correlated also with T_{air} (Figure 6.12), which explained between 26 and 42 % of the variation in LE during the growing season. For similar air temperature, LE was higher in the 2004/05 and lower in the 2005/06 growing season. In all years, the relationship between LE and T_{air} was fitted with an exponential curve. This suggests that the lack of high temperature (> 25 °C) has a limiting effect on ET (Figure 6.12).

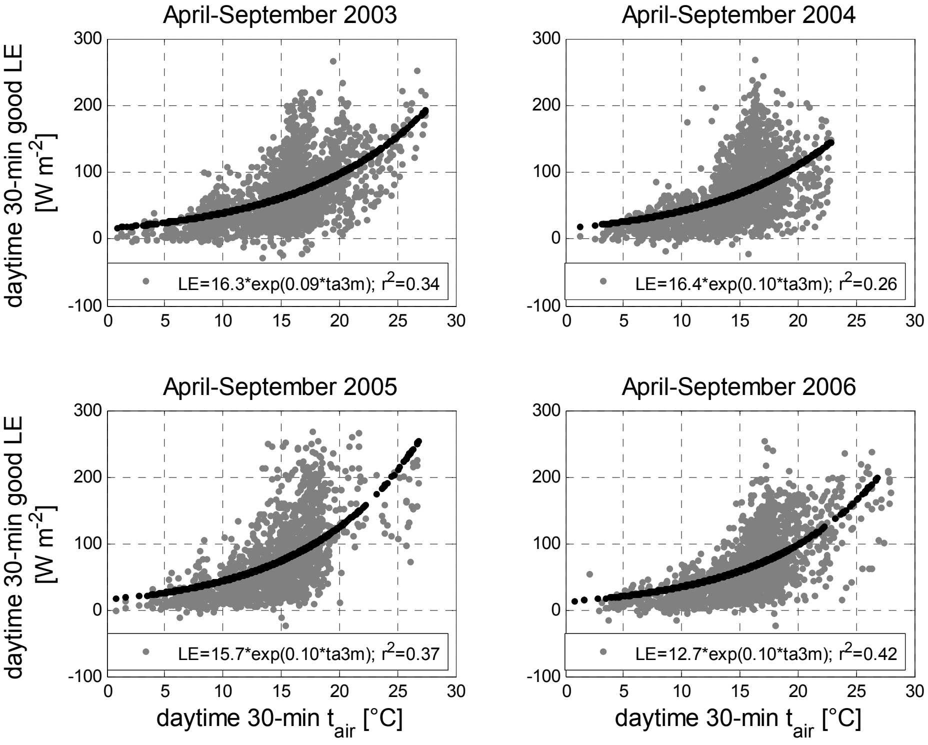

Figure 6.12. Relationship between 30-minute good LE and T_{air} in the four studied growing seasons.

Because of the high relative humidity, VPD in Irish climate is most frequently < 1.0 kPa (Jaksic et al., 2006). The latent heat flux correlated well with VPD through a linear relationship (Figure 6.13), which explained between 42 and 46 % of LE variation during the growing season (not shown). For similar VPD, LE was highest in the 2004/05 and lowest in the 2005/06 growing season. This linear relationship typically had a steeper slope at the beginning of the growing season, which decreased in summer and then September (Figure 6.13).

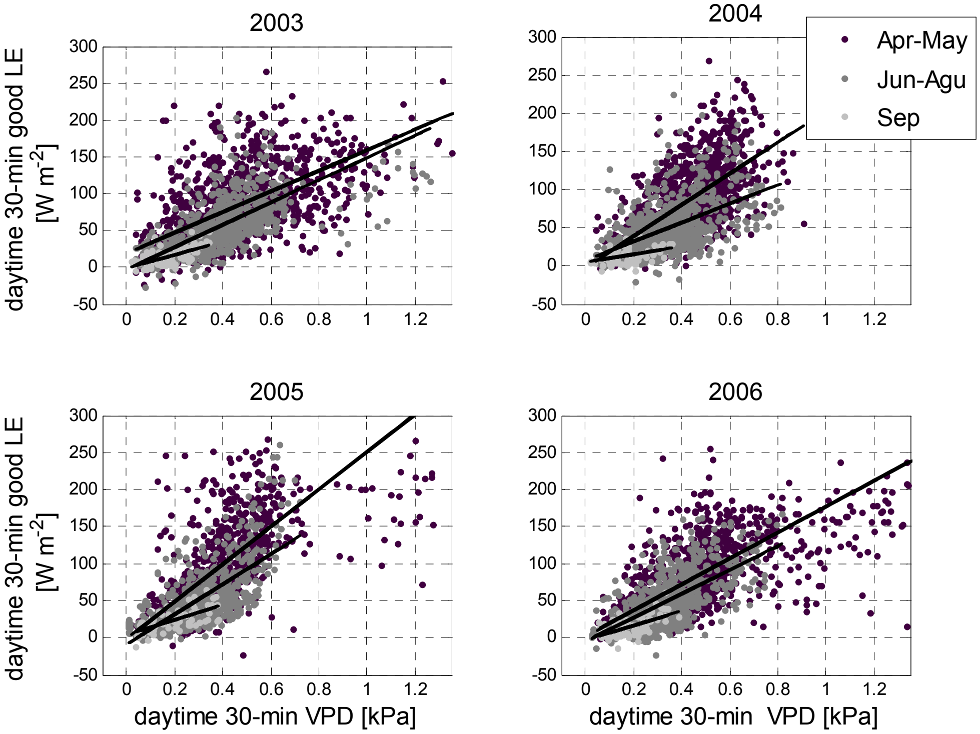

Figure 6.13. Relationship between 30-minute good LE and VPD in the four studied growing seasons. Data are divided in April-May, June-August and September periods and fit with different lines.

The Bowen ratio (β=H/LE) varied widely, between 0.5 and 2 during the growing season, but its average at around 1 was very similar in the four years, with lower values in the growing season with higher rain frequency (2005) and higher values in the growing season with lower rain frequency (2006, Figure 6.14).

α ranged between 0.4 and 1.2 and showed an opposite trend than β, being higher in the 2005 growing season (average of 0.93) and lower in the 2006 (average of 0.74) growing season.

The surface conductance (g_s) typically varied between 3 and 25 s mm $^{-1}$ and followed a similar pattern as α, being higher in the growing season with higher rain frequency (11.4 s mm^{-1} of average in 2005) and lower in the growing season with lower rain frequency (6.6 s mm^{-1} of average in 2006). β, α and g_s seem to be interconnected, as when a dry period followed rainy days (as in May-June 2003 and 2006, August 2003 and July 2006), β increased, while both α and g_s decreased (Figure 6.14). g_s was poorly related with LE (not shown), but appeared related with VPD, with g_s decreasing with increasing values of VPD (Figure 6.15).

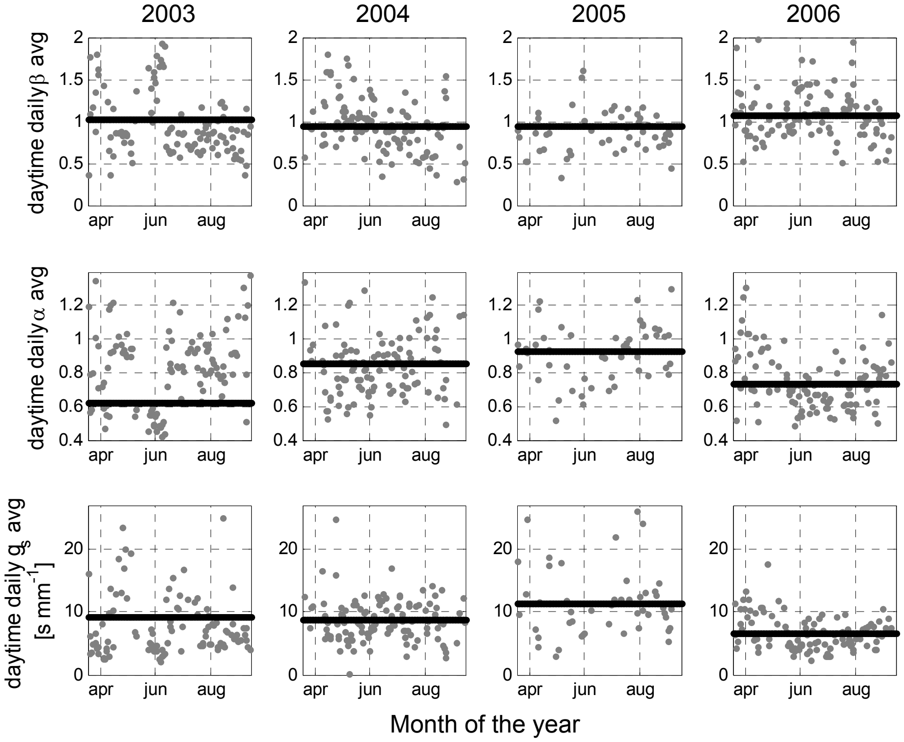

Figure 6.14. Daytime daily averages (solid line) of good 30-minute values between 10 am and 5 pm of β, α and g_s during the growing seasons of the four years. Only daily values when > 80 % of LE data between 10 am and 5 pm were good are shown.

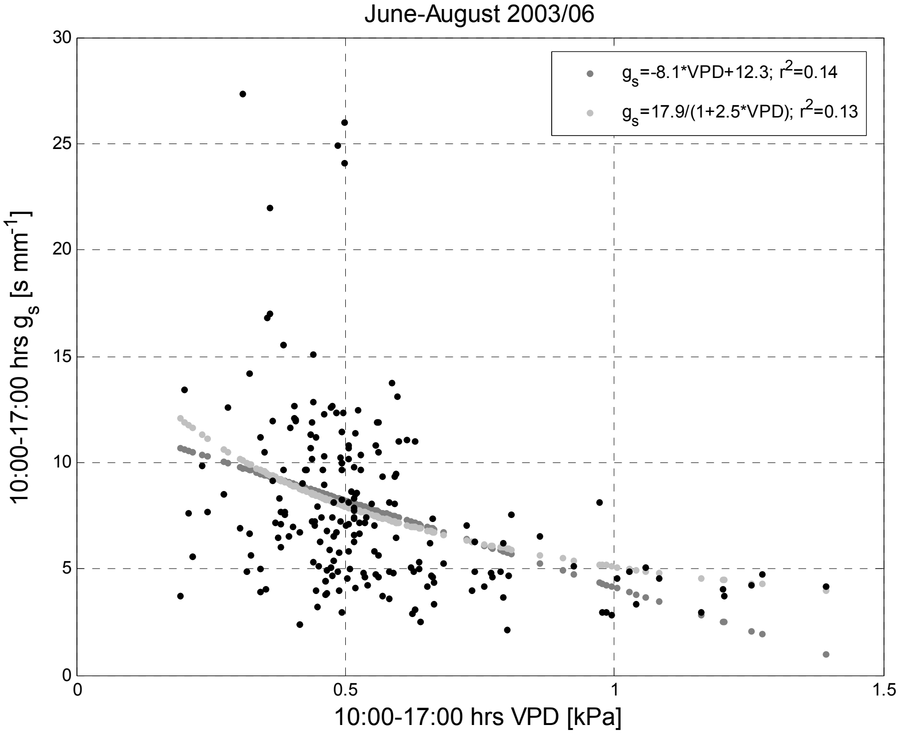

Figure 6.15. Relationship between daytime daily averages of g_s and VPD measured between 10 am and 5 pm. Only daily values when > 80 % of LE data between 10 am and 5 pm were good are shown.

The daily averages of energy fluxes in the four years show some interannual variation in R_n with consequent variation in the partitioning among the energy fluxes (Figure 6.16). The daily average R_n ranged between –60 W m^{-2} in winter and 200 W m^{-2} in summer. The daily average G varied between –15 W m^{-2} in winter and 20 W m^{-2} in summer. The daily averages of LE and H had their lowest values in winter, 0 and –50 W m^{-2} respectively, and their maximum in summer, about 80 W m^{-2} for both. LE and H were the components of the energy balance that varied the most in the four years. In 2005, the daily average LE was over 50 W m^{-2} for most of the summer, while it regularly dropped below this value in the drier summer of 2006, in parallel with a raise of H.

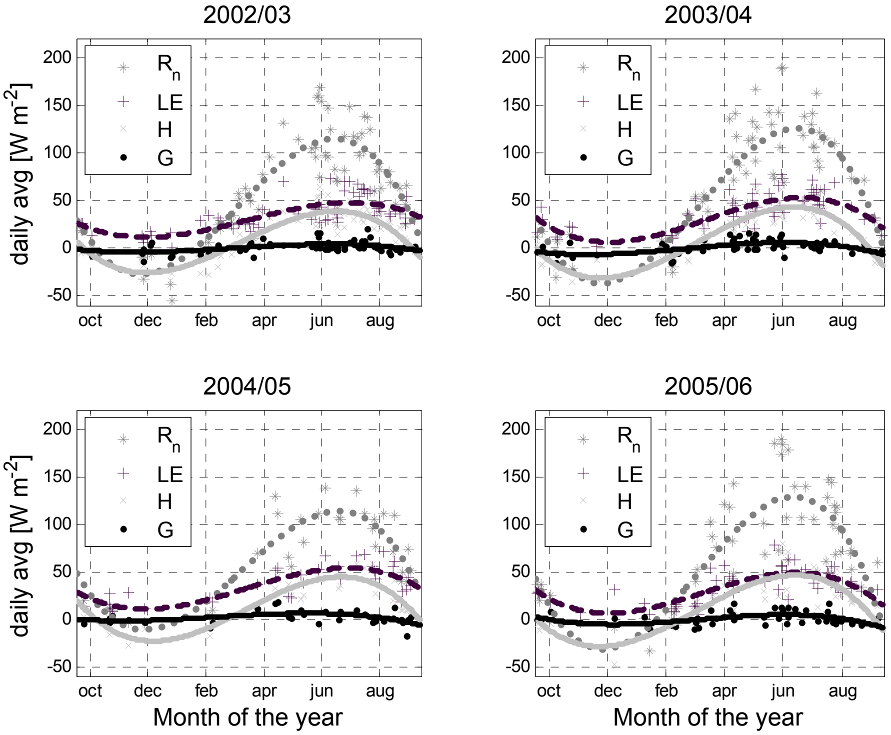

Figure 6.16. Annual variation in R_n, LE, H and G in the 4 studied years. Only daily values when > 75 % of LE data were good are shown.

In examining closure for the energy balance, we found that [H + LE] ranged between 64 to 68 % of [Rn – G] (see Figure 6.17).

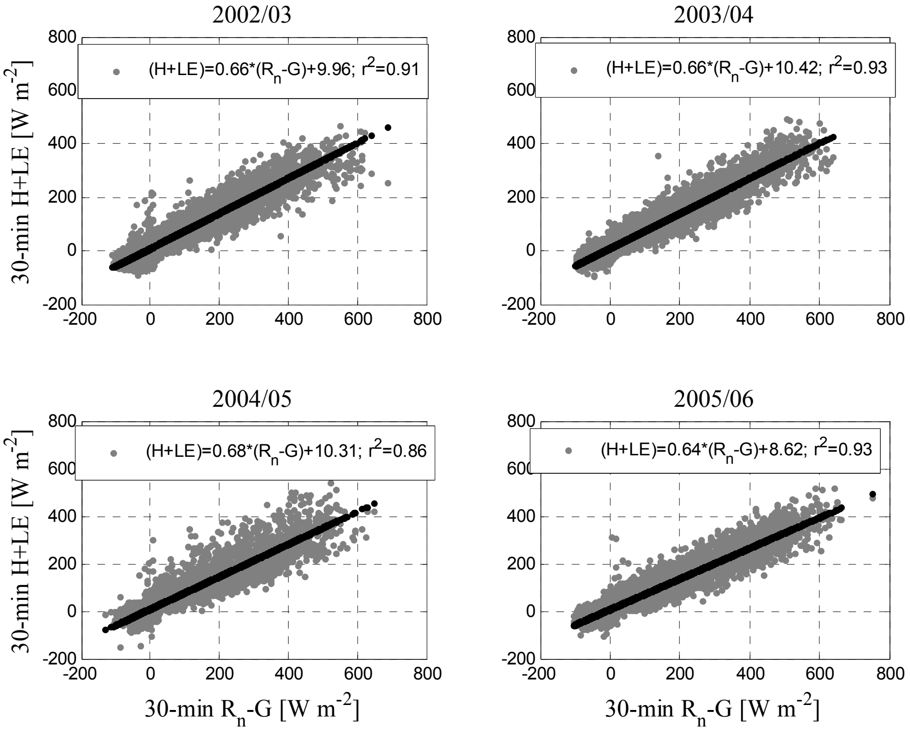

Figure 6.17. Annual energy balance closure in the 4 studied years. Only 30-minute values when LE was good are shown.

6.6 Discussion

6.6.1 Water balance

The hydrological year precipitation in the Glencar Atlantic blanket bog between the 1st October 2002 and 30th September 2006 ranged between 2428 mm and 2742 mm (Figure 6.4, Table 1) and was about twice the minimum required for the development of such ecosystems (Hammond, 1981; Taylor, 1983). At the nearby Met Eireann synoptic weather station at Valentia (30 km west of the study site), the rainfall for the period 2003-2006 was 8 % higher than its 30 year (1961-1990) average (http://www.meteireann.ie/climate/valentia.asp). The stream discharge and ET from the peatland were estimated as approximately 75 and 16 % of the total precipitation, respectively (Figure 6.3, Table 1). This partitioning of the water balance is similar to what was measured in a blanket bog in Newfoundland over short periods during the growing season (Price, 1991). The water balance in boreal raised bogs during the growing season is very different, with ET exceeding stream discharge (Kellner & Halldin, 2002). The annual water balance closure in the Glencar bog was within 10 %. The stream rating curve appears to overestimate the discharge during the heavy rain in November. The water overflow during days with up to 93 mm of rain was probably not fully directed in the small ditches along the road on the southern edge of the catchment, so that the catchment during these events might be bigger than expected. The lack of closure of the water balance is partly due to the underestimation of ET, as suggested by the underestimation of LE and H (Figure 6.17) and partly due to the increase storage in the peatland.

Evapotranspiration was only about 16 % of the total water input in the ecosystem (Table 1), which is far less than what observed in other ecosystems, grasslands 30 %, forest 60 % (Kiely, 1997), including boreal raised bogs, 54 % (Lafleur et al., 2005). This is partly due to the high amount of precipitation received by the ecosystem and partly to the low ET. Precipitation exceeded ET by 645 mm or more over the growing season period (April-September), more than three times the amount required for the development of Atlantic blanket bogs (Tallis, 1998).

6.6.2 Dormant season

Northern peatlands are typically located in boreal, sub-arctic or arctic regions, where climatic conditions are very different to that in our site. The winter in Glencar is characterized by mild temperatures, generally with no frozen soil or snow cover. The winter ET appeared very variable, with typical values higher than 0.5 mm day^{-1} and maximum values of almost 2 mm day^{-1} during days with high daytime T_{air} (Figure 6.4). This compares with typical winter ET between 0.1 and 0.5 mm day^{-1} from a boreal raised bog in Canada, which experience January temperature average of –10 °C (Lafleur et al., 2005).

6.6.3 Growing season

The Leaf Area Index measurements suggest that the growing season in 2005 started at the beginning of May, about one month earlier than in 2006 (Figure 6.6). The lateness of vascular plants leaf-out in 2006 was probably due to lower T_{air} and higher water table (Figures 6.7 and 6.8), which retarded soil warming (Appendix 1). Overall the growing season in Atlantic blanket bogs, despite the maritime climate, begins around mid-May as in boreal bogs (Admiral et al., 2006) and vascular plants complete their leaf-out only in late July (Figure 6.6). The LAI maximum in Glencar was 0.6 m^2 m^{-2}, which is less than half what observed in some boreal raised bogs (Shimoyama et al., 2004; Lafleur et al., 2005), but higher than in a Swedish bog and a Canadian rich fen (0.3, Kellner, 2001; Humphreys et al., 2006). The vascular plant cover to the ground in our site was quantified to be about 30 % (20 % of herbaceous plants and 10 % of evergreen dwarf shrubs) (Sottocornola et al., submitted to Journal of Ecology). Also the bryophyte occurrence is modest in Glencar, covering about 25 % of the peatland surface, half of them being bog mosses (*Sphagnum* species) and half brown mosses (Sottocornola et al., submitted to Journal of Ecology). The bryophyte plants in other bogs often cover almost completely the peatland surface (Glaser et al., 1990; Humphreys et al., 2006).

Precipitation in Glencar was more abundant and frequent during the growing season (Figure 6.7, Table 1) than in boreal raised bogs (Kurbatova et al., 2002; Admiral et al., 2006). The maximum water table fluctuation in Glencar was 17 cm below the surface whereas in boreal raised bogs, it typically reaches a depth between 20 and 60 cm below the peat surface (Kellner, 2001; Shimoyama et al., 2004; Lafleur et al., 2005).

The ET during the growing season was considerably lower in our study site compared to other peatland types. The mid-summer monthly mean ET in Glencar ranged between 1.3 and 1.8 mm day^{-1} (Figure 6.5), which compares with values between 2 and 3.3 mm day^{-1} of boreal raised bogs (Kellner, 2001; Kurbatova et al., 2002; Lafleur et al., 2005; Humphreys et al., 2006). The typical maximum daily ET in Glencar was between 2.5 and 3 mm day^{-1} (Figure 6.5), while it was between 4 and 5.5 mm day^{-1} in boreal raised bogs (Shimoyama et al., 2004; Lafleur et al., 2005). The lower ET in Glencar is likely explained by the lower plant occurrence (Figure 6.6), lower vapour pressure deficit and lower summer T_{air} than in boreal raised bogs (Figure 6.8), while R_n values appear to be similar (Figure 6.16) (Kurbatova et al., 2002; Shimoyama et al., 2003; Shimoyama et al., 2004; Admiral et al., 2006).

β was usually higher in spring and then decreased during the summer (Figure 6.14) as observed in other bogs (Lafleur et al., 1997). In Glencar, β was on average about 1 in the four growing seasons of measurements, which is considerably higher than what observed in other northern peatlands. β varied between 0.60 and 0.70 in a Siberian bog (Shimoyama et al., 2003) and averaged 0.45 in a subarctic wetland in Canada (Eaton et al., 2001). α averaged 0.79 over the four growing seasons in Glencar (Figure 6.13), which is generally lower than what estimated in other northern wetlands; higher values than 1 were measured in a subarctic wetland in Canada (Eaton et al., 2001), about 0.8 in a Swedish raised bog (Kellner, 2001) and 0.97 in a Canadian sedge fen (Lafleur et al., 1997). Similar values as in our Atlantic blanket bog were found in a patchy mire, with value around 0.63 (den Hartog et al., 1994).

6.6.4 Evapotranspiration mechanism

A poor relationship between ET and water table (Figure 6.9) is normally observed in northern peatlands (Lafleur et al., 2005; Humphreys et al., 2006). In a boreal raised bog, ET was found to be independent of water table except for very high and very low depth (Lafleur et al., 2005). These two water tables were respectively interpreted as the depth where the water table drops below the reach of mosses and of vascular plants (Lafleur et al., 2005). The ET in Glencar did not show any variation with water table, neither at higher or lower depth (Figure 6.9). The latter suggests that the water table in Glencar did not drop below the vascular plant root zone so that vascular plants were likely never water limited (Figure 6.7). More puzzling is the lack of ET increase with higher water table. Firstly, this is possibly due to the paucity of mosses able to draw water from the top few cm of soil. Secondly, since the hydraulic conductivity in blanket bogs does not decrease sharply with depth (Holden & Burt, 2003) as happens in other peatland types, the water from deeper peat layers is not retained more strongly by the soil than the surface peat water, so that ET from deeper layers is not retained more than from superficial peat layers.

Evapotranspiration in the Glencar Atlantic blanket bog ranges from 0.36 to 0.49 of PET (Figure 6.10). This ratio is typically lower than in boreal bogs (Kellner, 2001; Lafleur et al., 2005), probably because of the lower plant cover and consequent low transpiration. A low ET/PET ratio in peatlands was suggested to be caused by a decrease in ET due to a mulching effect by litter on the ground (Kurbatova et al., 2002).

The Latent heat flux related well with R_n (Figure 6.11) as was found in moss-dominated peatlands (Kellner, 2001; Kurbatova et al., 2002; Shimoyama et al., 2003) and in a high latitude sedge fen (Rouse, 2000). The LE appeared to be also controlled by T_{air} and VPD (Figures 6.12 and 6.13).

The relationship between LE and VPD in Glencar was typically stronger in April and May, than later in the growing season (Figure 6.13), indicating that VPD controls mosses and ground ET more than vascular plant transpiration, as observed by Admiral & Lafleur (2007). Surface conductance in our study site had high values (Figure 6.14) and showed a stronger response to VPD than in a range of Canadian peatland types (Figure 6.15) (Humphreys et al., 2006). Humphreys et al. (2006) suggested that different response of g_s to VPD are due to different types and abundance of the moss vegetation.

The peatland surface in Glencar is mainly covered by bare peat and brown mosses, which are less efficient in holding humidity and in withdrawing water from deeper peat depth than *Sphagnum* mosses (Hayward & Clymo, 1982). The typical maximum daily ET in a blanket bog in Newfoundland, which is largely covered by *Sphagnum* species, was 40-50 % higher than in Glencar, despite lower VPD, similar T_{air} and frequent fog events, which reduced the ET (Price, 1991; Price, 1992). The difference in ET between the two blanket bogs is therefore probably due to the different ground cover and peat surface wetness. This suggests that once the peat surface in Glencar dries out, the ground layer contribute little to the ecosystem evaporation and transpiration (Humphreys et al., 2006).

The Sensible and latent heat fluxes show a high seasonal and interannual variation (Figure 6.16) as in other peatlands (Kurbatova et al., 2002). The latent heat flux seems to be higher than H in wet periods while the opposite is true during dry periods. The energy balance closure was within 64 % for the four years (Figure 6.17). Closure is usually higher in other bogs, ranging between 80 and 90 % (den Hartog et al., 1994; Lafleur et al., 2003; Shimoyama et al., 2003). A full closure of the energy balance is very rare in peatland ecosystems, partly due to the difficulty to properly measure ground heat flux, which is expected to be very important in ecosystems with low vascular plant cover (Kurbatova et al., 2002).

6.6.5 Climate change - comparison between the four studied years

Climate change in Ireland is predicted to increase the mean monthly temperature between 1.25 and 1.5 °C throughout the whole year, with precipitation expected to decrease by 10 % in June and increase between 10 and 25 % in December for the 2021-2060 period (McGrath et al., 2005). Analysis of long term rainfall records across Ireland identified a trend of about a 10 % annual increase in the last quarter of the 20th century (Hoppe & Kiely, 1999; Kiely, 1999).

Since ET appears to be independent of water table (Figure 6.9), but dependent on atmospheric conditions (Figures 11, 12 and 13), it is no surprise that ET in June 2003 was much lower than in the other years due to lower T_{air}, VPD and R_n (Figures 6.6 and 6.7), despite the higher water table (Figure 6.7). Nevertheless, although the atmospheric conditions were more suitable for ET in summer 2006 than in summer 2005, ET was lower in summer 2006 than in summer 2005 (Table 1, Figure 6.8). This apparent contradiction is partly explained by the retarded vascular plants leaf-out and partly by the lower frequency of rain events occurred in summer 2006 (Figure 6.7). Infrequent rain events in 2006 likely caused the peat surface and the brown moss vegetation to dry and therefore contributed less to ET as is indicated by the lower slopes of the relationships between LE and VPD in 2006 than in 2005 (Figure 6.13).

The Glencar Atlantic blanket bog is a very rainy blanket bog. The ratio between ET and precipitation was very low and relatively stable during the four years, suggesting that this ecosystem might be relatively resilient to strong ecosystem change. Nevertheless, modification of the hydrological condition is expected to affect the chemistry of the bog water, which together will likely impact the vegetation composition and distribution (Sottocornola et al., submitted to Journal of Ecology). In addition, the Atlantic blanket bogs will possibly experience a decrease in ecosystem CO_2 uptake, due to water stress of the moss components caused by a decrease in the frequency of precipitation events during the growing season (See Appendix 1). On the other hand, the comparison between spring 2005 and 2006 suggests that higher temperatures and lower precipitation in the late spring may cause an earlier start of the growing season, with increased spring CO_2 uptake (Appendix 1).

Since ET seems to follow T_{air} trends, an increase of annual temperature will possibly increase winter ET. As well as ET, also winter precipitation are expected to increase (Hoppe & Kiely, 1999; Kiely, 1999; McGrath et al., 2005). The balance between the increase in winter ET and precipitation will determine the level of water table. Since water table influences soil respiration, the new balance between winter ET and precipitation will also determine the rate of winter CO_2 loss by the ecosystem.

6.7 Conclusion

Climate change will probably affect the energy and water budgets in blanket bogs in terms of predicted increases in temperature and predicted changes in precipitation patterns. The latter are expected to increase in winter and decrease in summer. These changes are not expected to produce major modification in the water balance and energy fluxes in the peatland. However, even small changes in energy and water budgets will probably have a strong impact on the ecosystem CO_2 fluxes.

Due to higher temperature and lower early summer precipitation, the growing season will likely have an earlier start, with consequent increase in evapotranspiration and increase in ecosystem CO_2 uptake in the spring. On the other hand, a reduction of the frequency of the summer rain events will cause a shortage of water on the soil surface, determining a decrease in evapotranspiration and water stress to the moss vegetation. This in turn will possibly induce an increase in soil respiration and a decrease in the moss vegetation photosynthetic ability, causing a decrease in the ecosystem summer CO_2 uptake.

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7 General discussion

7.1 The vegetation pattern

The Glencar peatland is a typical Atlantic blanket bog in the maritime region of Northwest Europe. Both the vegetation (Doyle & Moore, 1978; Doyle, 1982; Doyle, 1990) and the water chemistry (Proctor, 1992; Shotyk, 1997) are similar to that observed in other Atlantic blanket bogs in Ireland and Scotland.

The bryophyte cover is rather poor since its occurrence is limited to high lawns, the most common microform. The shrub component is small compared to boreal raised bogs (Lafleur et al., 2001b), while grasses and sedges are more common, although their extent of cover does not reach the vascular plants occurrence, typical for raised bogs (Shimoyama et al., 2004; Lafleur et al., 2005).

The bryophytes and vascular plant distribution is first explained by water table and then by pH and peat depth, respectively. Since both water table and pH are likely to be perturbed by climate change (Roulet et al., 1992; Laine et al., 1995), the distribution of bryophytes (which moreover seem to have a narrower niche than vascular plants), will likely be more affected by climate change than the vascular plants distribution.

The vegetation pattern in Atlantic blanket bogs was found to be influenced by the peatland centre-natural margin gradients as occur in other northern peatland types (Malmer, 1986), while no difference was observed along peatland centre-artificial margin gradients. This indicates that a human or animal disturbance to the peatland vegetation may be restricted to the damaged area. For conservation purposes this suggests that small blanket bogs may also be worthy of protection and that protection should include areas along the natural margins, where diverse vegetation, rich in biodiversity is likely to occur.

The C fluxes measured in Glencar (typical Atlantic blanket bog) may be considered representative of pristine Atlantic blanket bogs in Western Ireland. Nevertheless, since the variation in C flux patterns most likely coincides with the variations of vegetation communities, we recommend that the location of flux measurements in peatlands carefully considers the peatland centre-natural margin gradients, to capture the full range of C fluxes from the ecosystem.

7.2 The CO_2 fluxes

The interannual CO_2 flux pattern in Glencar from 2002 to 2006 ranged between –26.4 and –95.9 g C-CO_2 m^{-2}. This is similar to the CO_2 annual budget in a boreal raised bog (Lafleur et al., 2003; Roulet et al., 2007). The photosynthesis and respiration processes in the Glencar Atlantic blanket bog are smaller than that of the boreal raised bog. The high water table in Glencar slows the decomposition process while the lower plant occurrence and higher litter quality (Aerts et al., 1999) reduce the ecosystem CO_2 uptake.

The CO_2 fluxes exhibited some important annual variation over the 4-year period (Appendix 1). This variation is likely due to the varying onset of the growing season (Aurela et al., 2004) and to the precipitation regime in the different summers (Shurpali et al., 1995). The frequency of rain events likely influences the peat surface wetness, which in turn possibly affects the photosynthesis of the bryophyte vegetation.

7.3 Water and energy fluxes

Precipitation in the Glencar blanket bogs was abundant and frequent in every season with annual amounts ranging from 2428 to 2742 mm yr^{-1}. The water balance is dominated by discharge as previously observed in a blanket bog in Newfoundland (Price, 1992), while evapotranspiration was lower than in boreal raised bogs, probably because of lower plants occurrence, air temperature and vapour pressure deficit (Kurbatova et al., 2002; Shimoyama et al., 2003; Shimoyama et al., 2004; Admiral et al., 2006). In Glencar the annual evapotranspiration ranged between 13 and 17 % of annual precipitation. The relatively low evapotranspiration explains the high Bowen ratio observed in Glencar compared to other peatland types (Kellner, 2001; Shimoyama et al., 2003). Evapotranspiration in Glencar was lower than potential evapotranspiration as generally observed in bogs (Lafleur et al., 2005; Humphreys et al., 2006) and appeared independent of water table position. This suggests that vascular plants do not suffer water-stress. Evapotranspiration from the peat surface may be physiologically limited when not wet (Price, 1991) as suggested by the strong relationship between surface conductance and vapour pressure deficit. Water stress suffered by the bryophytes could partly explain the strong decrease of CO_2 uptake in the last year of measurement (the driest summer of the 4-year period).

Climate change will possibly have a small effect on the partitioning of available energy in heat fluxes and on the total annual or seasonal evapotranspiration. A bigger impact is to be expected if the frequency of the summer precipitation events decreases, causing water stress to the bryophyte vegetation with an accompanying decrease in the CO_2 uptake by the mosses.

8 Recommendations for future research

The results of the present study raise some issues and questions that we recommend for further investigation.

- The CO_2 flux is the main component of the C cycle in Atlantic blanket bogs (Laine, 2006). While smaller than CO_2 fluxes, the DOC export in some years has been observed to be as high as the net C accumulation. This has the effect of tipping bogs from C sink sites to source sites (Roulet et al., 2007). The measurement of DOC concentration in stream is therefore highly recommended alongside stream flow to estimate the annual DOC export.
- Methane release from peatlands can occur in the form of either a relatively constant efflux or ebullition (i.e. gas emission via bubbling). Ebullition can be a significant source of methane, up to one order of magnitude higher than constant efflux (Glaser et al., 2004). Since ebullition is unlikely to be captured by chamber measurements due to its episodic nature, the use of eddy covariance measurements for CH_4 is therefore suggested.
- CO_2 fluxes are highly variable from year to year (Appendix 1) so that measurements should continue for a longer period than four years, to capture the interannual variation in both fluxes and climatic conditions.
- While we are currently increasing our understanding of the carbon cycle, energy and water budgets in pristine blanket bogs, we cannot translate these findings to heavily disturbed peatlands or to peatlands under restoration. Measurements in these sites are therefore recommended.
- Since the Glencar peatland was identified as typical of Atlantic blanket bogs in western Ireland, remote sensing techniques could be used to scale flux measurements to regional and national level.
- To fully understand the mechanisms governing carbon, energy and water exchanges, a modelling effort is required. Modelling will further enhance our understanding of the processes occurring in the peatland, their connections with the vegetation and the potential impact of climate change on these ecosystems.

- While measurements performed with the chamber method and the eddy covariance open-path system gave similar CO_2 estimates, it is suggested a further comparison of the energy fluxes performed with a different system. The closed-path EC system installed in Glencar in autumn 2006 would be ideal for extending this study.
- The mechanisms governing evapotranspiration are still unclear. We hypothesised that the soil surface wetness might have an important role in controlling both the ecosystem evapotranspiration and the summer CO_2 exchange. Measurements of the soil surface moisture under bare soil, brown mosses and *Sphagnum* species are therefore recommended.
- The Glencar Blanket peatland is unique and is well instrumented for carbon, energy and water cycles. Consideration should be given to open up this site to national and international collaboration research. This will add value to the existing work

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Appendix 1

Four years of meteorological and CO_2 flux measurements.

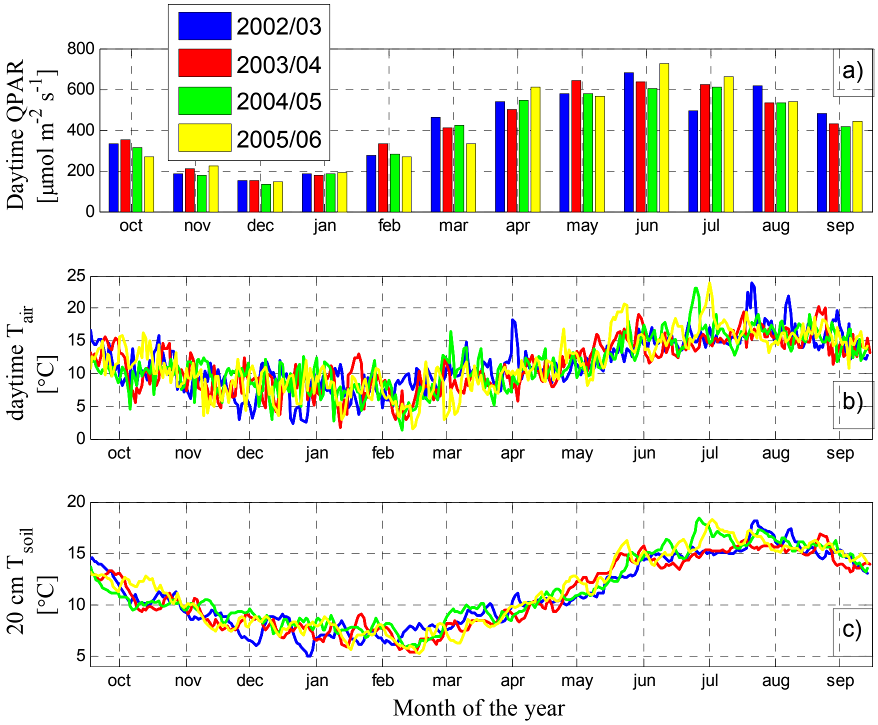

Figure 1 (a) Monthly daytime daily QPAR averages, (b) daytime daily T_{air} averages and (c) daytime daily T_{soil} averages during the four years 2002/03 to 2005/06.

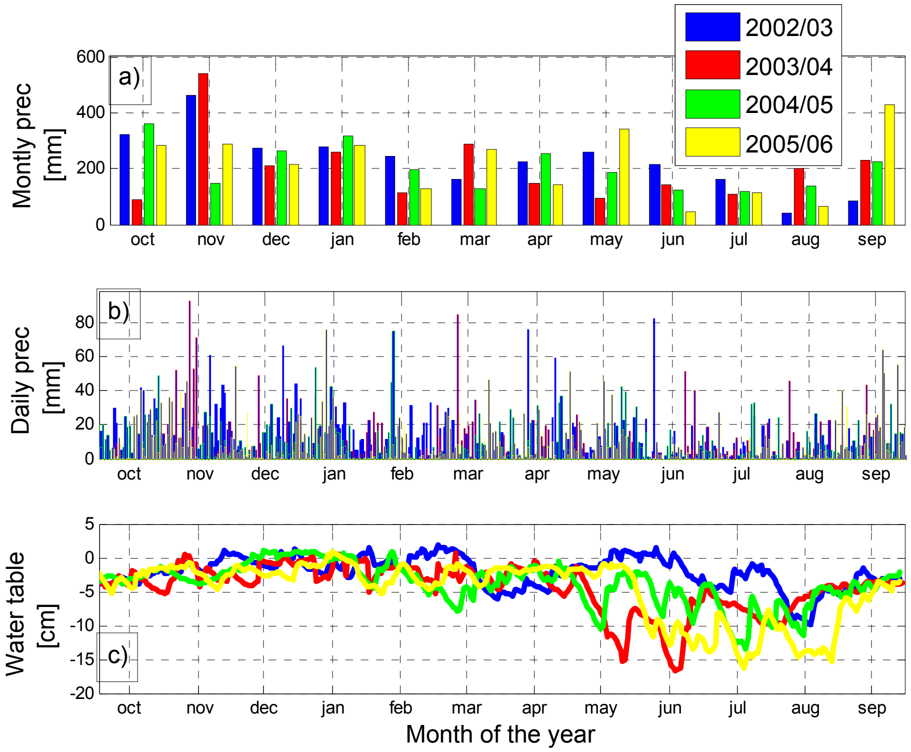

Figure 2. (a) Monthly precipitation; (b) daily precipitation; (c) Water table depth variation during the four years 2002/03 to 2005/06.

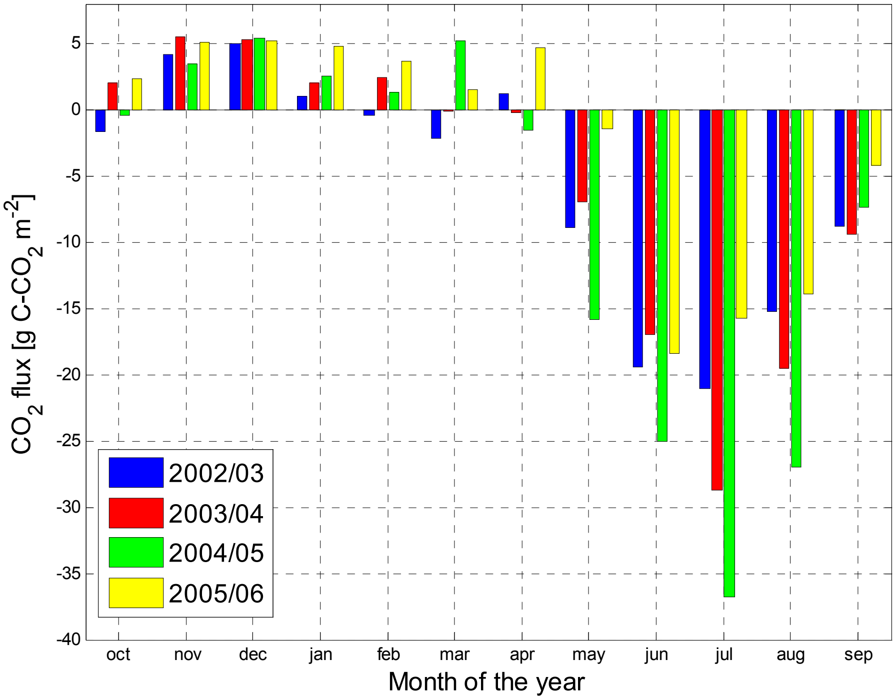

Figure 3. Monthly CO_2 flux during the four years 2002/03 to 2005/06.

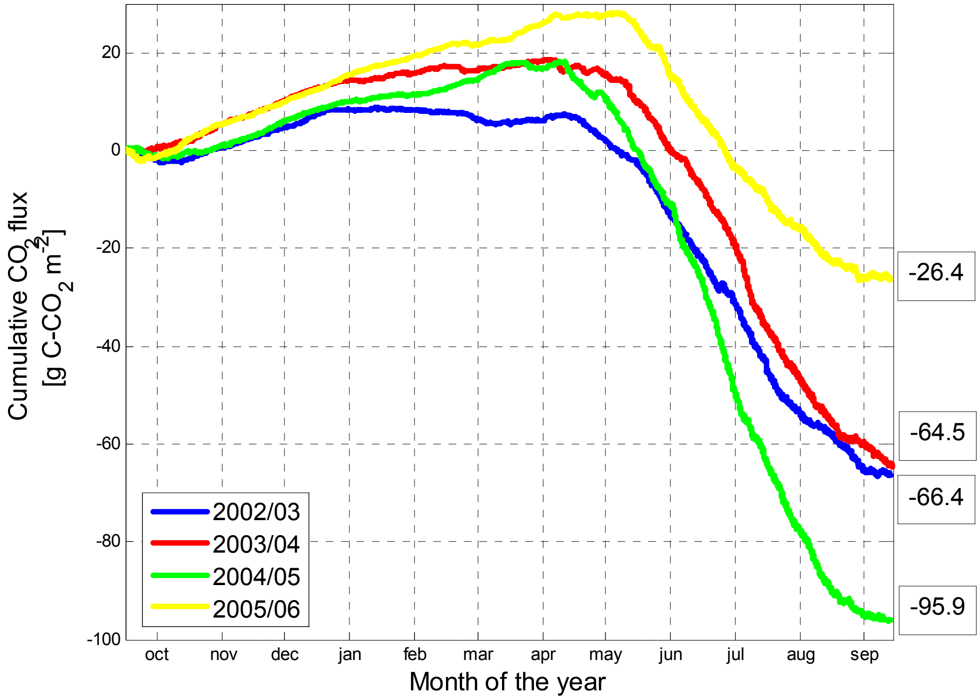

Figure 4. Cumulative CO_2 flux during the four years 2002/03 to 2005/06.

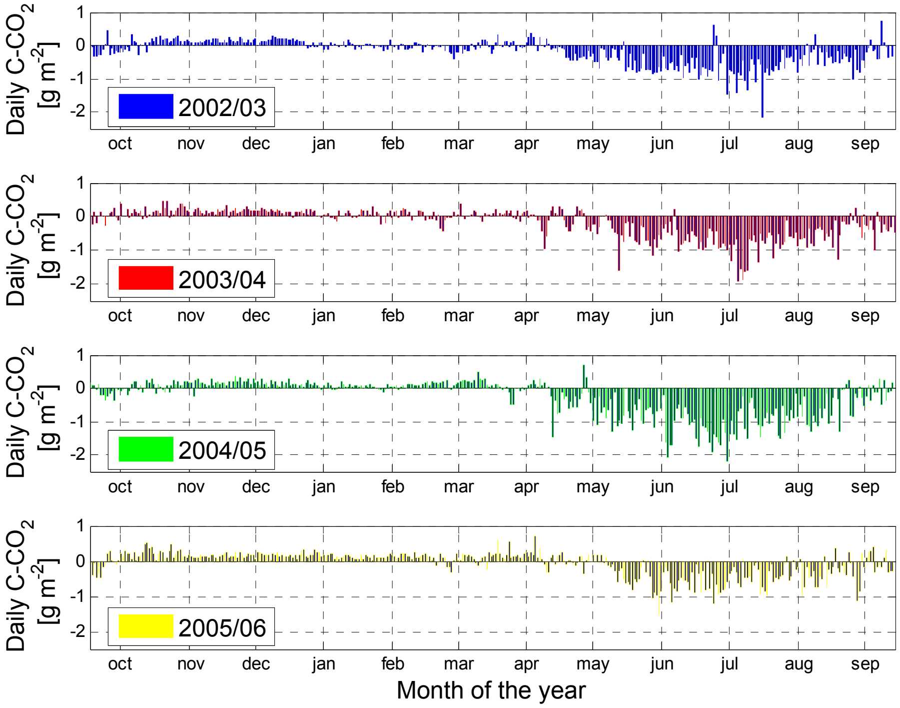

Figure 5. Daily CO_2 flux during the four years 2002/03 to 2005/06.

Appendix 2

Sottocornola, M. and G. Kiely (2005). An Atlantic Blanket Bog is a modest CO_2 sink. Geophysical Research Letters **32**(L23804): DOI: 10.1029/2005GL024731.

Appendix 3

Laine, A., M. Sottocornola, G. Kiely, K. A. Byrne, D. Wilson and E.-S. Tuittila (2006). Estimating net ecosystem exchange in a patterned ecosystem: Example from blanket bog. Agricultural and Forest Meteorology **138**: 231-243 DOI: 10.1016/j.agrformet.2006.05.005.