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Low-lying agricultural peatland sustainability under managed water regimes

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Abstract

The combined effects of ditchwater management regime and sub-irrigation spacing on water table fluctuation have been investigated for two low lying agricultural peatlands in England, West Sedgemoor in the Somerset Moors and Methwold Fen in the Norfolk Fenlands. The consequence of the resulting soil moisture regimes for microbially mediated mineralisation of soil organic matter has been examined on peat samples collected from the upper metre of peat profile from these two test sites.

It is shown that sub-surface tile spacing has a strong influence on the transference of ditchwater regime to the mid-tile point in the field. Where sub-irrigation spacing is greater than 40 m the mid-point water table falls to similar levels experienced without any form of sub-irrigation intervention. Where sub-irrigation is at 10 m intervals the mid-point water table was found to be close to the water regime maintained in the ditches.

Differences in field water-table level can lead to considerable variation in the matric potential experienced at different depths in the peat profile. As a consequence, peats at different stages of degradation (linked to depth) and under different land uses can exhibit variable physical and hydraulic properties. The von Post scale, which describes the degradation status of peats, has been linked to these physical properties but no simple model has been found between these properties and the von Post score. A good relationship has been found between saturated hydraulic conductivity and the van Genuchten alpha value which itself was related to the air entry value for all peats except the amorphous (unstructured) peat from Methwold fen.

The water management regime, in conjunction with variations in physical and hydraulic properties of different peat types, influences the peat microbial community structure. At West Sedgemoor those peats that are wetter have predominantly anaerobic species, whilst those in drier environments have a greater proportion of aerobic species. At Methwold Fen the variable nature of the water management strategy appears to have homogenised the microbial community throughout the entire peat profile, resulting in more aerobic microbes in the deeper peat deposits.

The type of microbial community and the degree of peat aeration dictate the efficiency with which soil organic matter is mineralised. Over the period October 2004 - July 2005 the rate of mineralisation in Methwold Fen peat samples averaged 0.40 g CO_2-C m^{-2} hr^{-1} in saturated samples whilst in drier peat it averaged 0.72 g CO_2-C m^{-2} hr^{-1}. This clearly demonstrates that a wetter peat profile minimises the rate of microbially mediated organic matter mineralisation.

Land use exerts an equally strong influence on microbial activity and can mask the true extent of soil organic matter mineralisation. Root exudates may offer an alternative source of organic carbon for microbial metabolic processes. Where the water table was maintained at 0.3 m below the soil surface respiration rates on grass covered West Sedgemoor peat samples was, at maximum, 1.46 g CO_2-C m^{-2} hr^{-1} whilst on bare Methwold Fen peat samples it was less, at 1.06 g CO_2-C m^{-2} hr^{-1}. After removal of all surface vegetation the average rate of respiration switched, with Methwold Fen peats exhibiting a greater rate of organic matter mineralisation (7.27 μg CO_2-C g $soil^{-1}$ hr^{-1}) than West Sedgemoor peats (3.8 μg CO2-C g $soil^{-1}$ hr^{-1}).

Sub-irrigation modelling, using a drainage theory based water table model, can adequately simulate the soil water balance. Coupling the output of a comparable hydrological model (SWAP) with a process based model of nutrient dynamics (ANIMO) demonstrates that under future climate scenarios closely spaced sub-irrigation could reduce the mineralisation of soil organic matter to the atmosphere and reduce subsidence by up to 2mm $year^{-1}$, thus reducing agricultural peatland contributions to greenhouse gas emissions and improving peatland sustainability[1].

Even partial aeration of a moist soil profile can lead to high rates of mineralisation. However, a combination of ditchwater management and sub-irrigation can, improve the sustainability of low lying peatlands if the management regime maximises the period of complete peatland inundation.

[1] Sustainability being defined as maintenance and/or improvement of peat soil resource quality and/or longevity through the reduction of present day rates of subsidence and mineralisation.

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Definitions

Acrotelm is the upper aerobic layer in peatlands.

Aerobic respiration is metabolic activity that employs oxygen to break down pyruvate by glycolosis. It is the most efficient form of metabolic activity.

Allochthonous deposits: occur when a material is washed or blown into position.

Amorphous peats (Moorsh) are those formed after the drainage / dehydration of peat. Increased aeration and differentiated humidity leads to the formation of a top layer of material (the Moorsh) with distinct physical and chemical parameters as compared to the parent material from which it was formed.

Anaerobic respiration is metabolic activity that utilises alternative electron acceptors to oxygen to break down pyruvate by glycolosis.

Arrhenius equation gives the quantitative basis of the relationship between the activation energy and the rate at which a chemical reaction proceeds.

Autochthonous deposits occur when soil material accumulates in situ.

Autotroph is an organism that uses inorganic carbon dioxide or bicarbonate as its sole source of carbon for growth and development.

Back-sight (BS) is the first reading from an instrument station.

Benchmark (BM) is a stable reference point. Usually used as the starting and finishing point when levelling.

Bog is the term for wetlands that accumulate acidic peat due to water supply being restricted to surface additions of rain and snow.

Carbon pool is another term for carbon reservoir. Different pools are identified according to the recalcitrance of organic matter to mineralisation.

Consolidation is the process whereby a soil decreases in volume in response to compressive stress applied over a long duration.

Datum is a reference surface to which the heights of all points in a survey or on a site are referred. Such datums' may be relative or fixed relative to a national height datum; defining the absolute height above Mean Sea Level. The UK national datum is at Newlyn, Cornwall.

Diagnostic horizon relates to a soil horizon having a set of quantitatively defined properties which are used in soil classification.

Drainable porosity (specific yield) is the ratio of the volume of water that a saturated soil will yield by gravity to the total volume of the soil (Bear, 1988).

Eutrophic peats are those with high nutrient status.

Evapo-transpiration is the loss of water from the soil both by direct evaporation and by transpiration from surface vegetation.

Fens are peatlands which receive water and nutrients from the underlying soil, rock and groundwater, as well as rain and snow.

Fen Carr is swampy woodland often found in association with fens and marshes.

Fibrous peats are structurally sound peats, having many plant fibres and wide pores. They constitute the bulk of ombrogenous raised bogs.

Foresight (FS) is the last reading from an instrument station.

Geogenesis is any kind of geological process relating to the origin and transport of sediments, to any form of sedimentation and to the growth and formation of peat.

Heterogeneous soils are those that are not of the same nature in type or quality.

Heterotrophs are organisms requiring organic substrates to provide carbon for growth and development.

Histosols are peat soils.

Homogeneous soils are those that are closely similar or comparable in kind or quality.

Humified peats (Sapric) are well decomposed amorphous peats that constitute the main body of many low moor peats.

Hydric soils are those that are formed under conditions of saturation long enough to develop anaerobic conditions in the upper part of the profile.

Hydrophobicity refers to the propensity of the physical properties of a molecule to repel water.

Intermediate sight (IS) is any sighting that is not a back-sight or foresight.

Lowland is land below 200 mAOD.

Mesotrophic peats are those where nutrient status is moderate.

Mesophilic organisms are those preferring moderate temperatures, with optimal growth between 20 to 45 ºC.

Metabolic activity is the biochemical modification of chemical compounds in living organisms and cells.

Methanotrophic bacteria are able to utilise methane as their only source of carbon and energy for metabolic activities.

Micro-aerophilic organisms are those requiring oxygen for growth at a level below that found in air.

Mineralisation is the process by which a substance is converted from an organic state to an inorganic state (e.g. organic matter to simple sugars, nitrates and carbon dioxide).

Minerotrophic peats are those of high nutrient status, where overlying vegetation is able to draw on underlying mineral deposits/groundwater.

Mire is the collective term for all peat forming ecosystems.

Moorsh peats are formed after the drainage / dehydration of peat. Increased aeration and differentiated humidity leads to the formation of a top layer of material (the Moorsh) with distinct physical and chemical parameters as compared to the parent material from which it was formed.

Muck soils are peat soils.

Oligotrophic peats are those which have poor nutrient status.

Ombrogenous peat formations normally overlying topogenous peat (low moor peat) in lowland areas.

Ombrotrophic peat is that which is nutrient poor and whose overlying vegetation relies on precipitation for their nutrients.

Peat is an accumulation of partially decayed vegetation matter.

Peat soil is that which develop in peat deposits. Peat soils contain a high proportion of organic matter and require a minimum thickness of peat. They need not, however, carry peat forming vegetation.

Peatlands are areas with a naturally accumulated peat layer at the surface.

Pedogenesis is the process by which soil is created.

Periplasm is the space between the plasma membrane and the outer membrane in gram-negative bacteria.

Phreatic zone refers to underground water below the water table.

Psychrophilic organisms are defined by Morita (1975) as those having optimum growth temperatures of <15 °C and upper limits of ~20 °C. But Feller and Gerday (2003) add the caveat that optimal growth temperatures are not necessarily optimal temperatures for metabolic processes.

Q_{10} is the change in rate of reaction with a 10 ºC change in temperature; given the activation energy of a catalyzed reaction according to the Arrhenius relation.

qCO_2 is the respiratory efficiency per unit microbial biomass measured as the amount of carbon lost due to respiratory inefficiency.

Ripening is synonymous with Pedogenesis and starts at the moment of drainage or oxidation of the soil. It is the result of both physical erosion and biochemical mineralisation processes.

Semi-fibrous peats (Hemic peats) are those where intermediate levels of decomposition have occurred.

Sesquioxides are oxides containing three atoms of oxygen and two atoms of some other compound.

Subsidence describes the motion of a surface as it shifts downward relative to a known datum (e.g. sea-level).

Sustainability is a systemic concept, relating to the continuity of social, economic and environmental aspects of human society. Sustainability aims to meet present needs and maximise present potentials of humanity whilst preserving biodiversity and natural ecosystems over the longer-term; so as not to compromise the needs and potentials of future generations.

Temporary Bench Mark (TBM) is a point (*e.g.* peg, nail, spike) placed to provide a temporary reference point.

Topogenous peats are those where a high water table is maintained by site topography. *e.g.* impervious soil basins.

Troposphere is the lowest layer of the atmosphere and contains about 95 per cent of the mass of air in the Earth's atmosphere. The troposphere is estimated to extend from the Earth's surface up to about 10 to 15 kilometres height.

Upland is land above 200 mAOD.

Vadose zone is the unsaturated portion of soil between the land surface and the water table.

Acronyms

CI	Confidence interval
DEFRA	Department of the Environment, Food and Rural Affairs
EAO	Environmental Assessment Office
EN	English Nature
ERDP	England Rural Development Programme
ESA	Environmentally Sensitive Area
GC	Gas chromatography
Gt	Giga tonne (10^9 t)
LSD	Least significant difference
mAOD	metres Above Ordnance Datum, Newlyn
MF	Methwold Fen
Mg	Megagram (10^6 g)
mg	Milligrams 10^{-3} g)
NFU	National Farmers Union
PCA	Principal Component Analysis
Pg	Petagrams (10^{15} g)
PLFA	Phospholipid Fatty Acid
PWP	Permanent wilting point (150 m pressure potential)
RSPB	Royal Society for the Protection of Birds
RWLA	Raised Water Level Area
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SRES	Special Report on Emissions Scenarios
TCD	Thermal Conductivity Detector
Tg	Teragrams (10^{12} g)
WRB	World Reference Base for soil resources
WRC	Water Retention Characteristics
WSM	West Sedgemoor
µg	Micrograms (10^{-6} g)
µl	Micro-litres (10^{-6} l)
µm	Micro-metres (10^{-6} m)

1. Introduction

1.1. Context

Globally, peatlands are estimated to account for more than 420 million hectares of land and contain 20–30 per cent of the world's organic carbon (Post *et al.* 1982, Gorham 1991**),** which Freeman *et al.* (2004) equates to 390 – 455 Pg (1 Pg = 10^{15} g) of organic carbon. Northern European peatlands are believed to account for a highly significant proportion of this total SOC stock, due to optimal climatic conditions for peat formation. In England and Wales it is estimated that peatlands cover an area of 520, 000 hectares (Taylor, 1980) and rank about 20th in the world for coverage of peatland. The National Soil Resources Institute (Bradley, pers comm) estimates that 12 per cent of the British rural land area is classified as peatland and contains 77 per cent of the total remaining British organic carbon stock.

Anthropogenic activities such as fossil fuel burning have long been considered the most important contributor to increases in atmospheric CO_2 concentration. Previous works had concluded that terrestrial carbon stocks provided a long-term sink for carbon, and hence assumed that soils did not make a significant contribution to atmospheric CO_2 concentrations. However, more recent studies (Freeman *et al.*, 2004) have questioned the stability of such carbon stocks under changing anthropogenic activities. Indeed, studies by a considerable number of workers (Woodwell *et al.* 1978, Gorham 1991, Zimov *et al.* 1999, Houghton and Woodwell 1989, Moore 2002, Kirk 2002, Lal 2004 and Bellamy *et al.* 2005) suggest that loss of carbon from soil systems is equally as important as other forms of CO_2 emission. The considerable variation in estimates of the net terrestrial contribution of CO_2 to the atmosphere has been demonstrated by Woodwell *et al.* (1978), whose estimates range between 2,000 and 18,000 Tg C year^{-1}.

1.1.1. Agricultural Peatlands

Extensive drainage of UK peatlands for agricultural production is the type of activity that has exacerbated the rate of degradation and loss of organic carbon from peat resources to the atmosphere. The Environmental Assessment Office (EAO, 1999) estimated that in total the UK has seen a 90 per cent loss of blanket bog and a 98 per cent loss of raised bog due to such activities.

The proximity of low-lying peatlands in England to major conurbations and the relative ease of drainage operations on such flat-lands have meant that historically these areas have been the first to be drained for intensive agricultural production. Such intensive land use has required deep drainage and hence, to date, the rate of subsidence of low-lying peatlands has been much greater than experienced elsewhere (Armstrong and Castle, 2000).

Drainage for any form of agricultural activity increases soil aeration and indeed, the initial ripening (biochemical oxidation) of soil for agricultural exploitation is a pre-requisite to successful agricultural activity. Such soil aeration is further enhanced by tillage procedures, which provide optimal environmental conditions for aerobic microbial mineralisation of SOM. This enhances the release of soil organic nutrients that are essential for crop growth. In peat soils, though, such continued ripening completely changes the soils texture and structure; causing dramatic changes in soil hydrology and associated nutrient dynamics. Investigating the inter-relationships between soil hydrology and soil ecology to quantify the degradation of organic matter may provide a means of modelling peatland degradation scenarios in the future.

1.1.2. Soil water management

Controlling agricultural soil water conditions generally relies on some form of drainage and irrigation scheduling. The majority of such irrigation operations are surface based systems that maximise efficiencies of water use. Generally, surface irrigation strategies allow the soil water content to decrease to a set level before crops are re-irrigated. This type of system is therefore unable to provide continuous long-term stability of the soil water content (Weatherhead and Danert, 2002). For peatlands, such fluctuating soil moisture conditions are liable to enhance aerobic microbial activity in the soil; ensuring greater microbial access to the organic carbon deposits in peat as a source of energy for metabolic activity.

Water-table management provides another means of controlling soil moisture and has been defined as *"the operation and management of the ground water-table level to maintain optimal soil moisture conditions for plant growth whilst maintaining water quality"* (Morris *et al.* 2004). In this respect managing the water-table level relies on the installation and management of a ditch infrastructure. The system may be further enhanced by the installation of a network of sub-surface pipes running from the ditch into the field. However, there are limitations to the use of such water-table management, as the area must be flat, and even then fields often require further levelling to ensure viable sub-irrigation.

1.1.3. The meaning of peatland sustainability

The soil moisture regimes experienced by different peatlands vary dramatically, both spatially and temporally. However, the soil moisture regime remains of fundamental importance to soil carbon cycling processes in peatlands; impacting on the soils physical and biochemical attributes and, ultimately, on the cause of organic matter mineralisation; microbial metabolic and respiratory activity.

Environmental conditions, peatland type, land and water-management history and current practices all have an influence on the water regime imposed on a peatland and hence dictate the degree of physical and biochemical perturbation experienced. Indeed, by its very nature, any form of agricultural activity cannot be conducive to the long-term sustainability of peatland resources as only the complete cessation of large-scale intensive agricultural activities on peatlands would significantly impact on the rates of degradation encountered. Realistically, the cessation of intensive agricultural activity on all low-lying peatlands is not a viable medium-term proposition. The most pragmatic solution is to develop and enhance existing agricultural management practices. Sustainability of agricultural peatlands cannot, therefore, ascribe to the 'Brundtland' definition of sustainability (World Commission on Environment and Development, 1987) *"to meet the needs of present without compromising the needs of future generations"*. Rather, the aim is to prolong the useful agricultural lifespan of such a soil resources[2], as proposed by Joosten and Clarke (2002).

[2] Sustainability being defined as maintenance and/or improvement of peat soil resource quality and/or longevity through the reduction of present day rates of peatland subsidence and mineralisation.

Though drainage practices on low-lying peatlands certainly influence the rate at which such peatland degradation and loss occurs, water-table management also has implications for land access. To achieve the common aim of sustainability, hoped for by all stakeholders (land-managers, drainage engineers, conservationists), any such water-management intervention must be compatible with the proposed land-use and the prevailing soil and environmental conditions if it is to be successfully adopted.

1.2. Broad aim

The broad aim of this thesis is to determine whether enhanced water-table management can further improve the sustainability of low-lying agricultural peatlands by decreasing the physical degradation and biochemical mineralisation of the organic carbon stocks they contain.

1.3. Broad plan

To research previous literature on the subsidence of drained peatlands and the physical and biochemical properties of such soils. Subsequently, to develop an appropriate plan to investigate the importance of changing soil moisture conditions on the physical and biochemical degradation rate of a range of such peats from low-lying agricultural peatlands in England.

2. Literature review

This review of the consequence of previous peatland drainage, of soil organic matter degradation and of water management practices provides an overview of the work that has informed the direction of this thesis. More detailed accounts of specific subjects are generally confined to relevant chapters, though where appropriate; the founding principals underpinning certain topics are also described here.

2.1. Loss of organic carbon from terrestrial soil systems.

Lal (2004), estimates that since the start of the industrial revolution there has been a 20-fold increase in the long term average terrestrial CO_2 emissions; adding a total 160 Gt of CO_2 to the atmosphere over the last 200 years (*i.e.* about 8 Gt yr^{-1}). However, Lal (2004) also states that of this additional 160 Gt that 136 Gt (+/-55 Gt) results from increased terrestrial ecosystem activity and that soil systems account for about 78 Gt (+/- 12 Gt). Of soil systems, Lal (2004) attributes one third to soil degradation and accelerated erosion and <u>two thirds to mineralisation</u>. However, Lal (2004) believes that percentage attributed to soil systems could be dramatically reduced if present water management practices were improved.

2.2. Overview of peatland degradation and loss

The drainage of peatlands for agricultural or commercial exploitation are the primary causes of degradation and loss of peat resources (Andriesse 1974, Driessen and Rochimah 1976, Schothorst 1977, Hutchinson 1980). Previous research has shown that intensive land-use leads to two types of change in peat soil organic matter. Firstly, physical degradation and secondly biochemical mineralisation of organic matter (Schothorst 1977, Lucas 1982). Additionally, there have been two scales of investigation. At the field-scale the combined consequence of degradation and loss has been monitored through changes in surface elevation (subsidence) whilst soil survey has recorded changes in peat humification. At the micro-scale studies of physical degradation have considered changes in soil physical properties whilst investigations of biochemical mineralisation have used rates of microbial respiration as a proxy for organic matter losses. Such peatland degradation and loss at both the macro- and micro-scale therefore need to be considered in the low-lying agricultural peatland context.

2.3. Overview of water-table management

There is a large body of work on the general topic of water-table fluctuation (Hubbert 1940, Gardner 1958, Gardner and Fireman 1958, Brooks and Corey 1964, Mualem 1976, van Genuchten 1980). Both the practical and theoretical aspects of land drainage have also received considerable attention (Dupuit 1863, Forcheimer 1886, Hooghoudt 1940) whilst over recent decades considerable attention has been directed at the use of ditchwater control to manipulate water tables (Youngs *et al.* 1989, Armstrong *et al.* 1993). Similarly the use of sub-irrigation is well documented (Ernst 1975, Hooker 1991). This thesis incorporates such work; outlining the general principles of water-table management and the consequence of water-table fluctuation in peatlands.

2.4. Past peatland wastage under variable drainage and water-table management practices.

2.4.1. Globally

There are long records of subsidence of reclaimed peats in the Netherlands, where reclamation (drainage) started between the 9th and 14th centuries (Schothorst, 1977). However, probably the best records on subsidence are available from the much more recent reclamation of the Everglades in Florida, USA, where subsidence has been monitored from the beginning of drainage in 1924 (Stephens 1956 and 1974; Stephens and Johnson 1951; Stephens and Speir 1969; Stephens *et al.* 1984). Reports on subsidence also come from Africa (Euroconsult, 1984) and Eastern Europe (Murashko, 1969) and also from the tropical regions of South East Asia (Andriesse 1974, Driessen and Rochimah 1976, Driessen and Sudewo, 1977). From such works longer-term average subsidence rates have been shown to range from less than 1cm to more than 8 cm year^{-1}.

Records of peat subsidence in South East Asia indicated 0.5 to 1.0 m was 'lost' in the initial years after drainage, with a subsequent rate of less than 6 cm $year^{-1}$. Similarly, some peats in the Florida Everglades subsided by 1.8 m in only 54 years (1924 -1978) and other peatlands in California, USA subsided by 1.8 to 2.0 m in less than 30 years. However, there are some peats in the Netherlands that have only subsided by 2.0 m in about 1000 years.

The rate of peat subsidence in the Netherlands has remained relatively small compared with rates experienced elsewhere, possibly because the water table was maintained through the centuries at between 20 and 50 cm below mean field level for pasture use. More recently, deeper and improved drainage has led to increased yearly subsidence rates, ranging from 1.7 mm to 7 mm $year^{-1}$. Field experiments in the Netherlands indicate that a 40 cm draw down of the water level in ditches over a period of 20 years has resulted in a total surface subsidence of 23 cm. In the first two years the subsidence proceeded very rapidly, constituting 44 per cent of the 20 year total but subsequently decreased to the aforementioned constant of 7 mm $year^{-1}$. This initial rapid rate of subsidence after drainage is apparent in most countries. Equally, it is believed the larger rates of subsidence experienced in tropical regions is due to certain crops requiring a much lower water table (*i.e.* tree crops are often grown with extensive, deep rooting systems that demand deep drainage).

Snyder *et al.* (1978) undertook a comparison of subsidence rate under sugar cane, vegetables and pasture, using predefined water-table depths. This showed the annual rate of subsidence under sugar cane was 30 per cent less than under pasture or vegetable crops. In previous studies no conclusive evidence has been available to show that the type of crop has a direct bearing on subsidence rate. However, indirect effects like climatic conditions: rainfall, wind, evaporation and temperature are important parameters for calculating crop water requirements, with each crop having an optimum water-table level dependent on rooting habits, resistance to drought and inundation.

Sugar cane grown in the Everglades in Florida requires a water table between 75 and 90 cm depth for optimum growth; however, experiments suggest only a 5 per cent decrease in optimal yield when the water table was raised from 75 to 38 cm depth. This suggested that water-table management in certain circumstances could be gainfully employed to reduce subsidence if it could be shown that the longer-term benefits of soil resource management could offset the small decrease in short-term economic loss.

2.4.2. Low-lying English Peatlands

Based on a review of the England and Wales Soil Survey (Burton and Hodgson, 1987) and historical land-use texts by Darby (1956), the East Anglian Fens and the Somerset Levels and Moors are considered by many as the last extensive lowland drained peatlands in England. The predominant land-use in each region has, however, resulted in considerably different water-management strategies being adopted.

The major peatland area in the East Anglia is known as The Fenlands; spanning the counties of Cambridgeshire, West Norfolk, West Suffolk and Lincolnshire, whilst the peatlands in the South-West are found on the Moors of Somerset.

2.4.2.1. The East Anglian fens

Small-scale agriculture has been practiced in the Fens since the 12th to 14th Centuries. However, the drainage schemes in place were not integrated and peatland inundation remained prevalent well into the 17th century (Darby, 1956).

Research into the general rates of subsidence across The East Anglian Fens has been undertaken by a number of researchers (Fowler 1933, Hutchinson 1980) but the best-documented work remains that on Holme Post, at Holme Fen, which Hutchinson (1980) believes provides a 150 year record of peat wastage. After drainage of Holme Fen in 1850 a long post (Holme Post) was completely submerged into the peat, with foundations set into the underlying mineral deposit. Continued drainage of Holme Fen eventually led to the majority of the post being exposed (Figure 1).

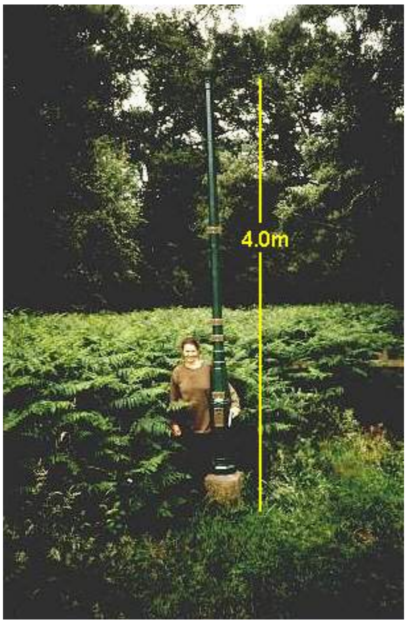

Figure 1: Holme Post - 4 m exposure after 150 years of peat subsidence (gradation and loss.)

Hutchinson (1980) demonstrates that there is a strong correlation between the record of peatland subsidence at Holme Fen and the successive reductions in water-table levels; which declined in response to the successive periods of pumped drainage (Figure 2).

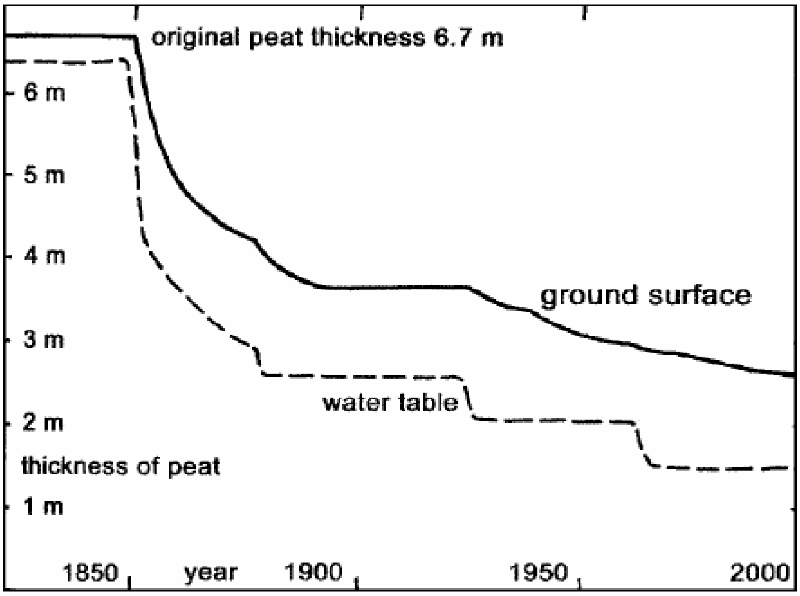

Figure 2: Retrospective determination of relationship between peat consolidation /mineralisation and the water table (Hutchinson, 1980).

2.4.2.2. Somerset Levels and Moors

The Somerset Levels and Moors cover an area of approximately 250 sq. miles. Over the last 17 years the levels and moors have been promoted by Somerset County Council as a unique wetland, requiring sensitive environmental management. The objective of such promotion has been to reconcile land-use with conservation of natural resources. The scheme gained backing from the Department of Environment, Food and Rural Affairs (DEFRA) and English Nature.

Currently, there are a number of factors affecting peatland stakeholders in the Somerset Levels and Moors, including:

- Water-level management
- Conservation of wildlife
- Amenity provision
- Maintenance and enhancement of landscape, including the after-use of ‘worked-out’ peat areas.

The Somerset County Council initiative recognised water-level management as the most critical factor given that the latter three issues are dependent upon the primary aim of conserving the uniqueness of the wetland environment. Therefore, in 1987, the Ministry of Agriculture, Fisheries and Food (MAFF) initiated the Environmentally Sensitive Areas (ESA) scheme. The Somerset Levels and Moors ESA extends over an area of 27,678 hectares of the central Somerset lowlands and forms the largest single remaining lowland wet grassland / marsh systems in Britain.

The ESA environmental objective (ADAS, 1996) concerning water-table management, remains:

“To enhance the wildlife conservation value of wet grassland without detriment to the landscape by maintaining higher water levels in the ditches and rhymes.”

- Ecoscope Applied Ecologists (2003)

Traditionally, water-table management in the Somerset Levels and Moors was to hold ditchwater levels lower in the winter months than in the summer months. This management strategy ensured the peatlands of the Moors provided a measure of flood protection during the winter months as the lower water table meant they could accept excess winter floodwaters. Conversely, the higher summertime water level was believed to reduce subsidence due to biochemical mineralisation, as anaerobic conditions militated against soil respiration. However, in 1988 the Royal Society for the Protection of Birds (RSPB) reported a sharp decline in the number of breeding waders on the Levels and Moors, possibly as a result of this water-management strategy. A set of 'trials' were set up to investigate whether changes in ditchwater management affected soil penetrability and hence wader bird success on the Somerset Moors.

In 1992 a revised ESA scheme was introduced where certain areas of land were designated as vulnerable habitats. A tiered water-management strategy was developed, with farmers on certain categories of land being able to join one of several water-management schemes. The 'Tier 3'* category required the greatest degree of ditchwater management but also provided the best financial incentive. It was determined from these Tier 3 trials that:

- higher winter ditch levels lead to higher field water levels
- higher spring and early summer water tables improve soil penetrability
- Tier 3 water levels were producing the desired effect for breeding waders

The RSPB adopted the Tier 3 management their land at West Sedgemoor in what is now designated as the Raised Water Level Area (RWLA). The Tier 3 land-management purpose is:

"To further enhance the ecological interest of grassland by the creation of wet winter and spring conditions on the moors."

*The Tier 3 management prescriptions were defined as:

- Do not carry out mechanical operations between 31 March and 1 July.

- Apply no inorganic fertilizer and do not exceed existing level of organic manure.
- Do not exceed grazing density of 1 animal per 0.75 ha from 20 May – 8 July.
- Do not make silage.
- Do not cut or top grass after 31 August.
- Do not use of herbicides to control creeping buttercup.

- ADAS (1996)

In 1995 the water-level management plan was drawn up for West Sedgemoor. Two of the key objectives were:

"To encourage the Operating Authority to provide water levels which sustain the health and hydrological characteristics of peat soils in the long-term, so as to avoid shrinkage, oxidation and sinking of field surfaces."

"To seek mechanisms for water-level management which (a) are more responsive to winter weather conditions and (b) through voluntary agreements allowing some areas to hold higher ditchwater levels each winter".

- West Sedgemoor District Drainage Board (1995).

Subsequently, a number of detailed appraisals of the water-management plan were commissioned (Hooper *et al.* 1996, Gowing 1996, Spoor *et al.* 1999). Gowing (1996) demonstrates the problems associated with the Raised Water Level Area (RWLA) on damage to the grassland species diversity, concluding that the prescribed water levels needed to be lowered during the early spring months and that increasing ditch spacing was required if valuable botanical species were to be preserved. Conversely, the work of Spoor *et al.* (1999) on safeguarding peat soils concluded that:

"…..in many field situations ditchwater management alone would be ineffectual [in conserving peat] unless considered in conjunction with ditch spacing and overall water availability."

"Peat wastage and deterioration is likely to increase significantly if summer water-tables fall below approximately 50 cm."

Such findings highlight the point that the needs of different stakeholder groups do not always coincide.

2.4.3. Summary

The above synopsis of research into global and local peatland subsidence rates and water-table management demonstrates that the type and intensity of agricultural land-use has been a significant driver in drainage and water-management practices. In England, though agriculture has been practiced on peatlands for a long time, the early peatland reclamation process was both localised and fractured. In certain areas, the lack of regional level planning and design of drainage infrastructure meant frequent flooding still occurred until quite recently and hence the rate at which these peatlands subsided and degraded was reduced, relative to peatlands under more intensive drainage management. A more detailed account of historical land drainage of the Fenlands and the Somerset Moors can be found at appendix 0.

2.5. Identifying peatland degradation through soil survey.

Peatland is not synonymous with mire (Proctor and Wheeler, 2000) because the term peatland includes areas that no longer carry peat-forming vegetation (though peat soils must predominate) whilst mires are defined by their continued peat accumulation (Mitsch and Gosselink, 1993). It is therefore necessary to be able to distinguish between peatlands that are 'hydrologically intact' and those that are not. Only the former will still actively develop peat.

As peatlands have been drained for agricultural/commercial purposes, there has been a continued change in their physical and biochemical properties. Indeed, as the organic matter oxidises/mineralises classification of an area once designated peatland may no longer be representative of that soil type. This is a significant reason for the difficulty found in the classification of peatlands, as research is often reliant on surveys that are no longer a definitive guide to peatland status.

Immirzi *et al.* (1992) in their work distinguished the following groups:

- Mire: the collective term for all peat forming ecosystems
- Peat: the partially decomposed remains of plants laid down in mires
- Peat soils: soils which develop in peat deposits. They contain a high proportion of organic matter and a minimum thickness of peat. They need not, however, carry peat forming vegetation. (see Histosols below.)

This categorisation of peatlands is useful to a certain extent but does not aid the soil surveyor or analyst in quantifying peat degradation.

Burton and Hodgson (1987) stated that pedologists view the formation of peat and peat soils as two separate processes. *"Geogenesis is that of peat formation whilst pedogenesis is that of peat soil development"*. The latter process starts to occur when oxygen enters previously waterlogged environments. Such a process is termed ripening (or degradation), and occurs through three media; physical, chemical and biological.

The first requirement is to assess whether the soil is indeed classified as a peat, or merely a mineral soil with high organic carbon content. This is readily achieved by 'loss-on-ignition' of a sample. All organic soils are identified as follows:

Peat Soils

- Peats: > 50 % organic matter (calculated by loss-on-ignition)
- Sandy Peats: 35-50 % organic matter with sand >50 % (equates to 20 % organic carbon).
- Loamy peats: <35 % organic matter (<20 % organic carbon)

Organic Soils are grouped as follows:

- Peaty Loams: >25 % organic matter (14.5 % organic carbon) if mineral fraction is >50 % clay.

- Peaty Sand: >20 % organic matter (12 % organic carbon) if mineral fraction has no clay or; proportional organic carbon content if clay content is intermediate.
- Organic (humose) mineral soils are grouped as follows:
- >10 % organic matter (>6 % organic carbon) if mineral fraction >50 % but 6 % organic matter (3.5 % organic carbon) if mineral fraction has no clay.

Having determined if a soil is indeed a peat the degree of soil degradation must be assessed. However, a continuum of peat type, ranging from completely fibrous parent material that has not degraded at all through to an amorphous and completely humified soil where no signs of the original plant material, can be recognised.

Pons and Zonneweld (1965) developed a method of determining the degree of 'ripening' using 'n'-values. The scale ranges from 0 (undried) to 10 (very strongly dried). Generally, values of $n<0.7$ indicate a ripe soil and values of $n>2.0$ indicate unripe. Drained peat soils tend to be in classes 5 to 7, whilst peats classed >7 tend to have been deep drained to >0.6 metres depth. However, when applied to soils other than humified peats, an allowance was required to account for the effects of the fibres in the different peat types. The more widely accepted method is that developed by von Post (1924) in which a scale of degradation is divided into 10 increments, H1 to H10 (appendix B.2), based on the amount of plant fibre, the remnant fraction after mechanical action and on the characteristics of fluid expressed after squeezing in the hand. Avery (1980) developed a modified version of the Von-Post humification assessment scale for field use. This condensed the von Post scale into 3 categories:

- H1 – H3 Light (Fibrous)
- H4 – H6 Dark (Semi-Fibrous)
- H7 – H10 Black (Humified / Amorphous)

Whilst individual soil horizons may conform to the aforementioned system of classification it is also the thickness of the upper soil profile that dictates whether a particular environment is classified as peatland.

Given that a generally accepted system of soil profile classification has not, as yet, been universally adopted (Dudal, 1990), attention has focussed on development of a *World Reference Base for soil resources* (FAO, 1998). Soils within this classification system have been grouped into 10 sets; which contain 30 soil reference groups. The *World Reference Base for soil resources* (WRB) classification refers to unambiguous diagnostic horizons. A more detailed account of the WRB classification system is given at appendix B. Prior to development of the WRB many countries developed their own soil classification systems. Such is the case in England and Wales, where field surveys follow standard procedures of The Soil Survey of England and Wales (Hodgson, 1997). There are 10 major soil groups in this system, with peats belonging to major soil group 10 (msg10), as opposed to the WRB group 1 (Histosols).

To qualify for major soil group 10 soils must meet both the following criteria:

- Either more than 40 cm of organic material within the upper 80 cm of the profile, or more than 30 cm of organic material resting directly on bedrock or skeletal material.
- No superficial non-humose mineral horizons with a colour value of 4 or more that extend below 30 cm depth.

At soil group level there are two primary divisions:

- Raw peat soils
- Earthy peat soils

The Earthy peat soils are characterised by a ripening of the topsoil, whilst raw peat soils are characterised by a lack of earthy topsoil. From an agricultural perspective, it is this latter group that is of interest. A more detailed account of The Soil Survey of England and Wales is at appendix B.2.

2.6. Causes of peatland subsidence, degradation and loss.

Peatlands subside after drainage not only because of a loss in volume but also because of a loss of organic matter. Schothorst (1977) recognized the following components in subsidence:

- Shrinkage due to physical processes. The withdrawal of moisture from the surface layers by evapo-transpiration may cause high moisture tensions in the root zone resulting in a decrease in volume of those layers above the phreatic surface.
- Consolidation or compression due to a mechanical process. When the groundwater level is lowered, the buoyant force of water is lost in the upper layers. The deeper layers then have to bear an increased weight of 1 g cm^2 cm of draw down of the groundwater level. This causes compression by the soil layers below the phreatic surface. Consolidation is often divided into a primary phase and a secular[3] phase. The former is largely a function of the rate of water escape from and through the peat mass. This can be very high in the initial phases of drainage because of the high permeability of raw peat. When permeability decreases as a result of consolidation the primary hydrodynamic phase becomes almost constant. Secular consolidation continues long after the primary phase has stopped to play its initial important role and may in the end account for half the total loss in volume.
- Mineralisation through biochemical processes (oxidation by microbial metabolic / respiratory activity).

It was previously accepted in the Netherlands that the decreasing volume of peat above the water table was controlled to a greater extent by shrinkage and consolidation than by mineralisation. However, Schothorst (1977), in studying Dutch peats, assessed that 20 per cent of the subsidence could be ascribed to irreversible shrinkage, 28 per cent to consolidation (subject to elastic rebound and recovery) and 52 per cent to mineralisation. These results are in agreement with the general findings elsewhere that mineralisation is the main cause for peat soil subsidence. It is generally

[3] The secular effect is stated by Koppejan (1948) to be attributed to the water that is bonded to the soil particles or to the connections between the soil particles or to both.

believed that consolidation and irreversible shrinkage gradually decrease from an initial peak but that mineralisation of organic materials continues at a more or less constant rate until a new lowering of the water levels in surrounding ditches is necessary.

Lucas (1982) expanded on the Schothorst (1977) categorisation, stating that subsidence was due to:

- Processes causing the removal of organic materials: oxidation, burning, wind erosion[4] and water erosion.
- Processes causing consolidation of materials: compaction, shrinkage and dehydration.
- Factors accelerating or influencing the processes mentioned under i. and ii. are: depth of drainage (height of water table), character of the organic materials, the cropping system employed including irrigation, and the climate, particularly the temperature regime.
- Geological subsidence is an independent factor that would also play a role when artificial drainage was not provided.

Similar to Schothorst (1977), Bouman and Driessen (1985) argued that the subsidence after drainage or reclamation was the sum of the effects of settling, shrinkage and mineralisation. The mathematical model developed by Stephens and Stewart (1977) to estimate subsidence was only valid for the mineralisation component, because it disregarded the effects of shrinkage and compaction. Bouman and Driessen (1985) preferred to employ two models to predict overall subsidence for tropical areas by fusing the Stephens-Stewart model for the mineralisation component and the Murashko equation (Murashko, 1969) for the consolidation component. By combining the two, total subsidence under tropical conditions could then be approximated.

[4] Wind erosion has been considered by a number of authors (Fullen 1985, MAFF 1985, WEEL 2000). The results indicating that soil water management has the capacity to reduce wind erosion by increasing adhesive bonding of granulated surface material.

2.7. The consequence of drainage practices on the physical and hydraulic attributes of peat soils.

2.7.1. Soil texture

Agriculture requires weathering and degradation of the mineral and organic matter to ensure the soil develops a good tilth. However, it is ultimately the texture (relative proportion of clay, sand and silt in the soil) that pre-determines the physical and hydraulic parameters of that soil and the texture class name of that soil (Elghamry and Elashkar, 1962). Unfortunately, as the major constituent of peat soils is organic matter, the means of peat soil textural classification relies primarily on the organic carbon content of the soil, which provides little indication of variations in the physical and hydraulic attributes of the soil relative to the degree of degradation. To differential between peat soils the work of von Post (1924)[5] is generally accepted as the main method for quantifying differences between peats. This can mean that a soil, though classified as peat, can move to another category of organic soil or, eventually, no longer be categorised as peat soil at all.

During degradation the mineralisation of organic carbon appears to follow Michaelis-Menton kinetics (CMARP, 1999), such that the rate of mineralisation and subsidence is proportional to the amount of carbon in the soil (Bonnett, 2005). Some workers (Paustian *et al.* 1997, Martens 2000) have reported that the type of SOC is of equal importance to the SOC content; as it determined whether a carbon energy source was readily available to soil microbes (lignin is a more recalcitrant energy source that cellulose). The type of organic carbon is dependent on both the original parent peat plant material and the period of prior degradation and is generally distinguished by grouping into one of several carbon pools.

2.7.2. Soil bulk and particle densities

Bouman and Driessen (1985) in their study of peatland subsidence rates indicated that bulk and particle density have a significant effect on subsidence of peatlands in the initial years, but that this effect slowly decreases with time.

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[5] See appendix B.2 (Table 17) for a fuller account of the von Post scale.

In assessing bulk density for peat soils in the UK, the standard for calculating peats carbon stocks previously relied on a value of 0.35 g cm^{-3}. However, subsequent research has suggested this value was too great, as it led to over-estimates of terrestrial carbon stocks.

Latterly, peat top-soils have generally been estimated to have a bulk density around 0.2 g cm^{-3}, and even lower for basin and blanket peats (Milne and Brown, 1997). Andriesse (1974) reported mean bulk densities of 0.12 and 0.09 g cm^{-3} for fibrous Malaysian peats. Driessen and Rochimah (1976) findings were of similar magnitude; indicating that fibrous Indonesian peats commonly have bulk densities of less than 0.1 g cm^{-3} and those of the well decomposed humified peats have values greater than 0.2 g cm^{-3}. Tie and Kueh (1979) specifically mention the bulk density of well-decomposed humified peat in Sarawak. This peat, with a loss-on-ignition of 95 per cent, has bulk densities of 0.15 and 0.13 g cm^{-3} at depths of 0-15 and 15-30 cm respectively, both of which are very low. However, other workers have reported cultivated peat to have surface horizons (0-15 cm) with a bulk density of 0.35 g cm^{-3} and subsoil (45-60 cm) densities of 0.18 g cm^{-3}. These higher densities are believed to be caused by cultivation and compaction of the surface layers upon drainage. The combined effect of climate, height of water table and mineralisation means most tropical peats under natural conditions have surface horizons that are more humified than sub-surface layers and hence greater bulk and particle densities.

2.7.3. Porosity

The texture of a soil determines ratio of pore spaces to solids in a given volume of soil and hence the size and distribution of soil pores. However, soil structure is also influenced by aggregation of the soil; creating another hierarchy of macropores. van Genuchten and Wierenga (1976) describe porosity as:

- 'Intra-aggregate porosity' is the microscopic pore space created by the geometrical packing of individual soil particles.
- 'Inter-aggregate porosity' represents the pore space due to the arrangement of soil aggregates. It is created by shrinkage during soil drying; cultivation, and biological activity.

This classification of porosity is often considered as a dual porosity system and is well suited to peat soils. Drainage means that peats are initially subject to a decrease in Inter-aggregate porosity as shrinkage occurs and aggregates are drawn closer together. Changes in over-burden experienced by deeper peat horizons can also lead to consolidation and might also be considered as a decrease in inter-aggregate porosity. Equally, biochemical degradation and mineralisation of organic matter can cause collapse of both aggregate and particle structure; decreasing the intra-aggregate porosity. Such structural collapse can lead to an irreversible reduction in the capacity for the soil to hold either air or water. Conversely, swelling of a soil after rewetting is a phenomenon normally associated with the texture of a soil rather than an increase in its inter-particle pore spaces (often found with sesquioxides). Quantifying porosity of peat soils at any given pressure potential can therefore be confounded by shrinkage and swelling of the soil.

2.7.4. Shrinkage and swelling

General research that includes some aspect of soil physical properties often presumes the soil complex to be a rigid structure. However, Hooghoudt *et al.* (1961), like Pons and Zonneveld (1965), determined that physical ripening of peats often leads to irreversible drying; to the extent that peat soils are unable to reabsorb moisture to the same degree as virgin peat. This had strong implications for the water retention characteristics of peats exposed to excessive drying. Michel *et al.* (2001) by using the capillary method to quantify re-wettability relative to moisture content of decomposed peats also showed that the greater the degree of decomposition, the greater and more irreversible the degree of such shrinkage.

Research has shown that the resistance to re-wetting of peats appears to be related to bulk density of the soil, with irreversible drying being more marked in organic soils with lower bulk densities. Equally, there are reports that complete re-wetting occurs where soils have high bulk densities (greater than 4.2 g cm^{-3}). The inability of a peat to rewet can cause severe drought stress in shallow rooting crops. Coulter (1957) attributed the hydrophobic nature of dried peat to the presence of a resinous coating, which presumably forms upon drying. Coulter (1957) suggests this coating prevents the reabsorption of water. However, there is some doubt about this. For example, Driessen and Rochimah (1976) did not find such coatings in Indonesian peats. Lucas (1982) indicates that acid humified peats exhibited the greatest resistance to re-wetting because of their carboxyl and phenolic hydroxyl groups, and high lignin content. Consistent with this theory is the observation that changes in sphagnum peats are usually small because they are low in lignins, but that the condition is very marked in vascular peats with large pore spaces. Most tropical peats belong to the latter group. Other reports of re-wetting resistance include suggestions that there are adsorbed air films and iron coating around the organic particles.

Most organic soils display a degree of shrinkage when dried but also swell when re-wetted, unless they are dried to a threshold value beyond which irreversible drying occurs; at which point they tend to develop a marked decrease in their potential water retention capacity when rewetted. As the peats' structural integrity degrades under increasing pressure potentials, the reduction in soil pore size and total volume suggests that the pores are less likely to drain freely when subsequent matric pressures are experience by the peat. Whilst the water retention properties of the peat may increase with humification it is also the case that the total water-holding capacity will be reduced relative to the 'original' volume. However, organic soils appear to become less affected by such drying after they have been cultivated for some time. This is most likely related to gradual change from a fibrous to a more humified state. Lucas (1982) suggests that the amount of mineral matter and the nature of the decomposed organic material influence shrinkage most; with the wood content of the peat soil acting as a stable skeleton and reducing shrinkage of the whole. This may explain the large differences reported by Lucas (1982) between saw-grass peat (20-25 per cent shrinkage); semi-aquatic mucks (10-15 per cent); woody 'mucks' (30-50 per cent), and; mangrove mucks (40-50 per cent).

Research of hydrophobicity of peat soils has also concentrated on the contact angle between water droplets and peat samples. Bachmann and Van der Ploeg (2002) found there were considerable deficiencies in the current knowledge on the interaction of solid particle surfaces and the liquid phase of soil. Research was therefore undertaken to emphasise the impact of wetting angle on the re-wetting of dry soil and the impact of interfacial tension of the liquid phase in the three-phase system. Such work stresses that, at low water content, the transition from capillary-bound water to adsorbed water is of great importance on the rewetting process of dry soil. Through studying the hydric properties of peat soils Valat *et al.* (1991) found that cyclic wetting and drying produced peats that were more hydrophobic. Analysis of the contact angles on air-dried pellets determined this was more obvious for woody (122.1°) and herbaceous (116.8°) peats than sphagnum peat (110.9°).

2.7.5. Water retention characteristics

Water retention capacity values are reported to show marked differences for peat soils at various stages of degradation. The weight of water held in fibrous peat may be as much as 20 times the weight of the solid-particles, whereas that held in semi-fibrous peats may contain less than twice the soil's dry weight. However, if the water-holding capacity of a soil has been expressed on a volumetric moisture basis the differences in total porosity may be much less apparent. Thus, Tay (1969) suggests the difference between values of water-holding capacity should be expressed on an oven-dry weight basis, as the findings can then be used to distinguish between stages in decomposition and peat types. Using this method Tay (1969) determined values for Malaysian coastal peats (woody and fibrous) that contain 15 to 30 times their own weight in water, whilst Andriesse (1974), determined the water-holding capacity of West Borneo peats was in the range of 275 to 322 per cent; values which are considered low and which were probably related to cultivated peat with semi-fibrous characteristics.

2.7.6. Hydraulic conductivity

Early experimental work by Darcy (Warrick, 2002) pioneered the way we determine movement of water through the soil. The rate of water movement through the soil varies considerably as a function of soil texture, porosity and hydraulic pressure. Soils with low flow hydraulic conductivity can suffer from both soil-moisture deficit and water-logging, as water cannot move into or away from the area in question rapidly enough once drying or flooding occurs. Conversely, soils with high hydraulic conductivity may be able to overcome flooding issue but may be prone to rapid drainage.

Water flow occurs through, and is changed by, the following mechanisms:

- Hydraulic conductivity of peat soils varies significantly, due to soil layering (laminations); botanical composition and degree of decomposition.
- Unsaturated hydraulic conductivity: The rate at which water vapour will move through that fraction of a soil profile that is dominated by air filled pores spaces.
- Solute transport: hydraulic conductivity will affect leaching of nutrients and other complex organic compounds resultant of redox potential of a peat.
- Macro pore flow: macro-pores (continuous voids in soil), including structural shrink–swell and tillage fractures, significantly alter the hydraulic conductivity of peat, both laterally and vertically.

The rate of movement of water through the soil is highly relevant to drainage problems and is controlled by several factors. The type of peat, its degree of decomposition and bulk density combine to influence hydraulic conductivity and therefore provide a good basis for its assessment (Boelter, 1974).

In humified horizons of some Canadian peats very low permeability, of the order of 0.36 to 0.036 cm h^{-1} have been determined (Irwin 1968, quoted by Tie and Kueh 1979), which is less than that of many fine textured soils. However, Soepraptohardjo and Driessen (1976) reported rapid horizontal hydraulic conductivity but slow vertical conductivity for some peats in Indonesia. Lucas (1982) indicates that, in general, fibrous peats have moderate rates of water movement while decomposed and herbaceous peats often have low values. This corroborates the findings of Irwin (1968). Rates less than 0.36 cm h^{-1} are reported to be too slow for successful agricultural development. Laboratory studies on ‘mucks’ from Ontario, USA, give hydraulic conductivity values of 22, 18 and 4 cm h^{-1} for depths of 0-15, 15-30 and 30-45 cm respectively. Florida peat soils (12 - 21 cm depth) were found to have a hydraulic conductivity ranging from 29 - 67 cm h^{-1} depending on soil series. Though horizontal hydraulic conductivity rates are generally reported to be faster than vertical rates, Clayton *et al.* (1942), in a study of water control of the Florida Everglades, found that vertical movement was greater than horizontal movement and suggested this may be related to orientation of the saw-grass roots; which were generally vertical.

2.8. Peat soil respiration (mineralisation) and microbiology

Wardle *et al.* (2004) in their work on ecological linkages between above- and below-ground flora and fauna determined there to be strong mutual drivers controlling the cycling of nutrients, and that the different components of the soil food web showed a range of responses to the resource inputs because they were driven by both top-down and bottom-up processes.

Over recent years the quality of organic matter in the soil has become a key factor in considering the degradation potential of soil carbon stocks (Six *et al.,* 2002). The quality of organic matter could well determine the capacity for peats microbial degradation (microbial community structure, biomass and respiration rate). This may well vary according to the botanical composition and/or the differing degrees degradation of peat soils. Given the high organic matter content of peat the importance of recent research on carbon pools cannot be overstated (Fierer *et al.,* 2003).

2.8.1. Soil respiration

Soil respiration is the sum of heterotrophic (microbes and soil fauna) and autotrophic (root) respiration. Schlesinger and Andrews (2000) state that the global emission of CO_2 from soil is one of the largest fluxes in the global carbon cycle. Oechel *et al.* (1993) found that a relatively small increase in the rate of soil respiration could be sufficient to switch an ecosystem from a carbon sink to a carbon source of CO_2 to the troposphere.

Early laboratory studies of the biochemical mineralisation of SOM (Waksman and Stevens 1929, Waksman and Purvis, 1932) found different rates of decomposition in peats of different chemical composition and also in peats containing different micro-flora and micro-organisms. Samples of Florida low moor peat were found to have decomposed by 15 per cent at 28 °C over 18 months under optimum moisture conditions of 50-80 per cent. Above and below this moisture range decomposition rates were found to diminish rapidly. Panikov (1999) and Leiros *et al.* (1999) also indicate that nutrient availability is a strong determinant of microbial community structure and activity. Leiros *et al.* (1999) state that the type and rate of biochemical activity ultimately determines the degree of mineralisation (biochemical oxidation) of peat soils. Moore and Dalva (1997) when researching the potential of peat soils for CO_2 exchange in aerobic and anaerobic laboratory incubations showed that at incubation temperatures of 15 and 20 °C the rate of CO_2 production ranged between 0.07 and 5.0 mg g soil^{-1} d^{-1}, for anaerobic and aerobic production rates respectively. CO_2 production rates were greatest in the upper peat horizons and appeared related to botanical origin of peat. Aerts and Ludwig (1997), during investigation of respiration in eutrophic and mesotrophic peat columns, found that a high static water table produced high rates of anaerobic CO_2 whilst a slightly lower static water table (10 cm below the surface) led to an equal or lower CO_2 emission. It therefore seems likely that variations in biochemical composition and water-table level of peat soils affects the rate at which microbial activity degrades the physical structure of such soils.

Soil temperature is cited by numerous workers (Hanson *et al.* 2000, Kätterer *et al.* 1998) as one of the major driving forces behind soil respiration rates. However, Fang and Moncrieff (2001) report that though soil respiration rates do increase exponentially with temperature no optimal soil respiration rate could be determined with soil temperatures below 32 °C. This was contrary to the findings of other workers, which Fang and Moncrieff (2001) believe is due to the use of reconstructed soil samples in previous investigations.

2.8.2. Substrate induced respiration and microbial biomass.

Many soil microbes are cellular in structure. As individual microbial cells grow larger they eventually divide into new individuals. Microbial growth is often defined, not in terms of cell size, but as the increase in the number of cells that results from such cell division. However, the quantity of microbial cells is not an indicator of actual soil respiration, as the majority of such microbes are in a dormant stated. Substrate Induced Respiration (SIR) was forwarded by Anderson and Domsch (1975) as an alternative means to calculated microbial biomass. The method relies on the rate of microbial respiration from a given weight of soil being determined on the addition of an energy source to the soil. However, the respiratory activity (CO_2 efflux) per unit weight of dry soil must be determined within a given time span; prior to an exponential phase of growth associated with the standard bacterial growth curve of microbial reproduction. Anderson and Domsch (1975) developed an empirical formula to convert substrate induced respiration to a microbial biomass.

2.8.3. Nutrient status

The degradation of organic matter not only concerns the release of carbon from the soil but the release of other nutrients into the soil complex. All soils contain considerable quantities of nitrogen in organic forms; both as components of the SOM and in the form of newly added crop residues. The decomposition of this organic matter by micro-organisms releases (mineralises) the nitrogen bound up in organic forms, making it available for plant uptake. However, nutrient cycling can also lead to eutrophication of waterways which can cause switches in the biological community, causing release of algal toxins and clogging such waterways with algal blooms.

Many nitrogen compounds (NO_2, NO_3, NH_4) occur in the mobile phase whilst the majority of phosphate compounds tend to bind to sedimentary particles. The relative availability of nutrients in both soil and water phases dictates the potential competition for scarce resources between soil microbial and plant communities. This has ramifications for the degree of microbial respiration in the soil. However, relatively little work on the flow of nutrients (Nitrates, Ammonium and Phosphates) has been undertaken in drained peatlands. Baird and Gaffney (2000) do demonstrate that in artificially drained peatlands of the Somerset Moors the potential for changes in hydraulic potential gradient associated with seasonal drainage can lead to periods of greater risk from nutrient leaching into the surrounding ditch systems. Baird and Gaffney (2000) believe this could have dire consequences for those peatlands that are species rich and of high conservation value.

2.8.4. Microbial community structure.

Fertile organic soils may contain 10^{12} bacteria, 10^4 protozoa, 10^4 nematodes and 25 km of fungi. However, dependent upon the soil composition, the fraction of soil surface area covered by these microbial populations may only be 6-10 per cent of the total surface area (Young and Crawford, 2004). The texture and structure of a soil determines the physical habitats of different soil systems and so determines the characteristic spatial clustering of microbes within that soil complex (Young and Crawford 2004). Work by Nunan *et al.* (2003) on the relationship between physical and ecological soil characteristics has shown that the distribution of microbes varies significantly from ordered to completely random, dependent upon spatial location (subsoil versus topsoil). This has implications for the nature of nutrient and organic carbon utilisation and mobilisation within the soil-plant-atmosphere continuum.

Obligate anaerobic bacteria are reportedly distinguished by the presence of two unusual types of phospholipid; the plasmalogens and the sphingolipids. Neither of these phospholipids is commonly found in either facultative anaerobes or aerobic bacteria. The most common means of classifying bacterial microbes is according to the Gram staining technique. This relies on the ability of a micro-organisms cell wall to retain a dye during solvent treatment. Those microbes having cell walls with a higher peptidoglycan and lower lipid content stain well and are classified as gram positive, whilst those with lower lipid content do not stain well and are termed gram-negative bacteria. In general, gram-positive bacteria have a thicker cell wall than gram-negative bacteria and produce spores enabling them to survive until more favourable conditions prevail. Gram-positive bacteria are believed to fill a niche similar to fungi in that they produce exo-enzymes and absorb nutrients from the extra-organismal environment (Prescott *et al.* 1996). In contrast, it is thought that gram-negative bacteria are better adapted to wetter environments (Hatori 1988, Petersen *et al.* 1997) due to their thinner cell wall and retention of digestive enzymes in the periplasm. Gram-positive groups of anaerobic bacteria have been identified by the presence of the cyclo-propane PLFAs (Ratledge and Wilkinson, 1988) whilst gram-negative obligate methanotrophic bacteria have tended to be classified according to their morphology as either type I or type II methanotrophs (Bowman *et al.*, 1991) and sulfate reducing bacteria according to the presence of the unique phospholipid fatty acid 10-Me16:0 (Dowling *et al*., 1986).

Whilst many methods exist to classify soil microbial communities many of the methods rely on staining or culturing the soil microbes. These methods have draw-backs in that many soil microbes are not cultivable. White *et al.* (1979) first suggested that living microbes could be identified by the lipid composition of their cell membranes. Separating and quantifying the living fraction of soil microbes from dead organisms is difficult with some microbial assays but analysis of cell membrane lipids overcomes this. This is because phospholipid fatty acids (PLFA) are metabolised by enzyme hydrolysis of the phosphate group rapidly after death of the cell (White *et al.* 1979). PLFAs are present in the lipid cell membranes of all living micro-organisms, many of which have distinctive PLFA patterns. Bacteria have a peculiarly diverse range of such PLFAs; consisting of different chain length fatty acids as well as branched and cyclic chains. Changes to the relative proportion of these PLFAs indicate a difference in the microbial community structure, with combinations of specific PLFAs acting as biomarkers for particular microbial groups. The relative abundance of these fatty acids can therefore be used as an indicator of the presence of specific groups of organisms that constitute a soils microbial community (Guckert *et al.* 1986, Ratledge and Wilkinson, 1988). Zelles *et al.* (1992) made a considerable contribution to identifying soil microbial community structures with PLFA analysis and a considerable number of researchers (Green and Scrow, 2000; Bossio and Scrow, 1998) use this method to assess the effects of environmental stress (such as moisture regime) on microbial community structure.

2.8.5. Summary of microbial respiration and community structure

It can be stated that soil moisture, nutrient status and carbon energy sources all affect the size and type of microbial community and their activity level and hence peat decomposition rates. Given that peatlands account for such a large proportion of terrestrial carbon stocks, the extent of soil respiratory activity in peatlands is fundamental to the carbon cycle and hence global warming. Both natural and agricultural processes rely on soil microbial metabolic processes to ensure the breakdown of organic matter and release of nutrients vital to plant growth. However, on established agricultural peat soils, achieving sustainable soil management requires a reduction in such aerobic microbial activity through management of soil moisture and temperature regimes during non productive periods.

2.9. Mitigating peatland erosion

DEFRA (2004a) report on the England Rural Development Programme (ERDP) indicates the deep peats occurring in the low-lying Fens are currently of grade 1 agricultural quality. They are used to grow a wide range of arable crops, horticultural and fruit crops. However, the peaty fen soils continue to shrink and suffer erosion; which threatens this land quality. DEFRA (2004a) further note that whilst there is a long-term detrimental implication for the environment, industry and agricultural interests, there are too many unpredictable variables involved in land management to develop long-term strategies and that research should focus on the medium-term implications, up to 2050, of peatland management. However, the paucity of recent information about degradation and loss rates of peat soils has been recognised by the UK government and, through DEFRA, have set out the following policy aims for peatland management in England (DEFRA, 2004b):

"Conserve a sufficient range, distribution and number of all peatland habitats, representing part of the critical natural capital of the country; and promote the wise use of the wetland resource within the nation's peatland heritage."

"Avoid wherever practicable the destruction of important archaeological remains in peatland."

2.10. Water-table management

2.10.1. Soil water movement and storage capacity

Quantifying the soil water balance is generally based on empirical models of gains and losses of water to the soil system. The water-balance model reported by Risser (2005) demonstrates the theoretical simplicity of changes in water storage:

$$\Delta S = P - (RO + ET + DP)$$

Equation 1: Empirical water-balance model.

where ΔS is change in soil water storage, P is precipitation, RO is run-off, ET is evapo-transpiration and DP is deep percolation

The rate of change in soil water storage is dependent on gains and losses of water to the soil system. Where bottom and side boundary conditions preclude seepage additions of water to the system are readily quantified by rainfall inputs, but the rate at which losses occur depends on the rate at which water can move through the soil. Figure 3 depicts changes in water-table level due to simplified gains and losses of water to a soil system.

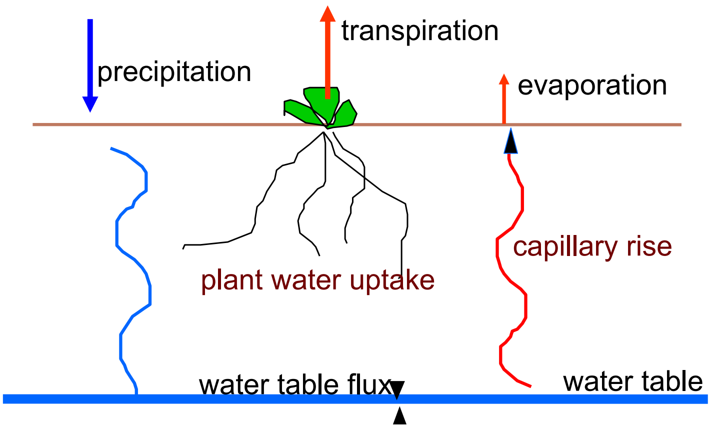


Figure 3: Schematic of gains and losses of water to the soil system.

Where the soil is saturated then the soil textural properties and pressure potential gradient determine the rate of such water movement through the soil. Above the water table and capillary fringe the rate of flow has proven more difficult to quantify. However, early work by Brooks and Corey (1964) and Mualem (1976) on unsaturated flow in the vadose zone enabled van Genuchten's (1980) development of a closed form equation to quantify unsaturated flow.

2.10.2. Irrigation

Irrigation can be considered as another form of input to the simple water-balance model. Most conventional surface irrigation systems allow the soil water content to deplete to a certain level before it is 'topped-up' (generally 50 per cent of field capacity). This type of irrigation therefore leads to fluctuating soil moisture conditions that are reported to exacerbate the rate of SOM degradation (Leiros *et al.*, 1999 and Albrecht *et al.,* 2000). Conversely, sub-irrigation maintains a water table in dynamic equilibrium and avoids such fluctuating soil moisture conditions. Careful design of this type of water-table management system therefore has the potential to militate against differences in the hydraulic properties of peat soils by taking into account differences in the hydraulic conductivity and specific yield of different peats that result from shrinkage and consolidation. Stabilising soil moisture conditions with sub-irrigation also has considerable potential to reduce the biochemical degradation and mineralisation of SOM; by preventing the occurrence of optimal soil moisture conditions for aerobic microbial activity.

2.10.3. Sub-irrigation

To install and manage a sub-irrigation and drainage system requires a network of ditches and water control mechanisms around each field. Sub-irrigation is most frequently employed on flat-lands, as the level of land dictates the ability to use pressure head gradients to regulate the flow of water from the ditch system into the sub-surface system. Such systems are concerned with both saturated lateral flow below the water table and unsaturated upward flux through the vadose zone (Warrick 2003). The control of the ditchwater level is therefore of paramount importance because the pressure head maintained above the sub-irrigation system dictates the pressure head in that system and hence the potential lateral flow of water below the phreatic surface. Figure 4 demonstrates the relationship between the ditchwater level and the field water table midway between adjacent sub-surface pipes and the means of water-table observation.

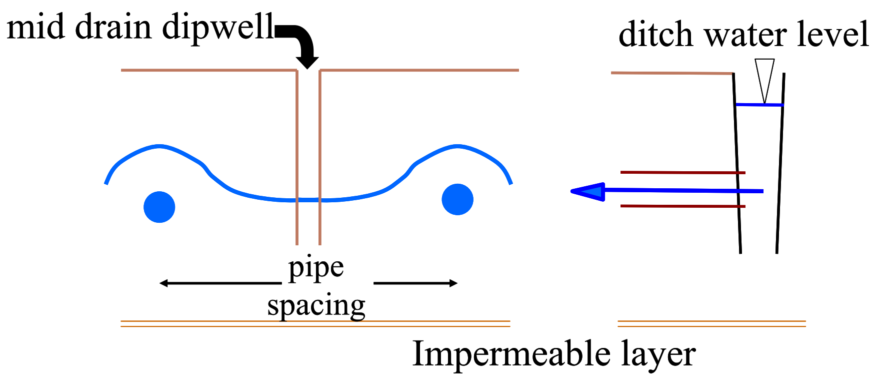


Figure 4: Schematic of sub-irrigation.

The spacing between adjacent sub-surface pipes is a crucial determinant of the effectiveness of the sub-irrigation system in maintaining a constant water table. However, a combination of factors influence the required depth and spacing of lateral pipes, including regional variations of inputs and losses of water due to precipitation and evapo-transpiration; the effectiveness of surface drainage; specific yield; depth to an impermeable underlying boundary; thickness of individual soil horizons and hydraulic conductivity. To optimise sub-surface system spacing according to the desired soil moisture conditions therefore requires knowledge of the soil's hydraulic properties, of the ditchwater-management practices, climate variables and crop water requirements.

2.10.3.1. Theory

Drainage theory quantifies the relationship between pipe flow and water-table position relative to the pipe. The early drainage theory of Dupuis and Forcheimer (Bear, 1988) considered land drainage to an idealised ditch system, with the assumption of lateral flow only. Knowledge was advanced when Hooghoudt (1940) considered drainage through sub-surface radial pipes. Hooghoudt (1940) found the pipe's radial shape led to an increase in the length of flow streamlines to the pipe and hence an increase in entry resistance to the pipe. For water to drain at the same rate experienced in the Dupuis-Forcheimer solution required a greater pressure head difference between the field and the pipe system. In considering the mathematical solution to such radial flow convergence losses Hooghoudt (1940) found that convergence losses were a function of the thickness of soil between the radial pipe and an underlying impermeable layer and by substituting a term he called equivalent depth (d) into the Dupuis-Forcheimer drainage equation the effect of convergence losses on pipe flow could be discounted.

The Hooghoudt (1940) equivalent depth theory was equally relevant to the study of flow from radial pipes (sub-irrigation). Ernst (1975) developed Hooghoudt (1940) theory for the sub- irrigation case in which the boundary ditch maintained a high pressure head that allowed water to flow from the ditch into the field with an evaporative flux upward through the water table. The maximum change in water-table height generally occurs at the furthest point from a pipe, midway between adjacent sub-surface pipes. It has been shown that this is dicated by the lines flow between adjacent pipes (flownets).

For modelling purposes water movement in the vadose zone is often assumed to occur through an idealised homogeneous, isotropic soil so that it can be solved using a variant of Richard's equation. However, modelling such soil-water movement in the vadose zone is often difficult because soil systems rarely consist of such a homogeneous profile with horizons of similar physical properties. Equally, divergence of the actual rate of evaporation from the potential rate of evaporation can occur if the unsaturated hydraulic conductivity in the vadose zone is limited by the depth of the water table (Penman 1940, Klute 1952, Philip 1955, Gardner 1958, Gardner and Fireman 1958, Childs 1969). In heterogeneous peats the vertical rate of saturated flow varies considerably from the lateral rate of flow and, in addition the rate of evaporative flux upward through the vadose zone varies according to the pressure potential. However, the Allen *et al*. (1998) consider the Penman-Monteith model the most rigorous method for quantifying the combined effects of evaporation and transpiration (evapo-transpiration) for irrigation and drainage purposes.

Typically all water balance equations make simplifying assumptions that aid the mathematical solution of sub-surface drainage and irrigation problems. Though in practice a steady state water table is not generally found, the assumption that a series of steady state situations occurs enables the use of empirical solutions like the Ernst-Hooghoudt equations to mathematically solve the effects of pipe spacing on water-table depth. The generic nature of the Ernst-Hooghoudt equation allows for a number of soil specific parameters to be adjusted to improve modelling outcomes relative to changing environmental conditions. Hooker (1991) demonstates the Ernst-Hooghoudt equation provides a robust method for sub-irrigation system design in peatlands. Hooker (1991) states that a strong correlation exists between observed water tables and those predicted by Ernst-Hooghoudt equation for sub-irrigation systems placed at 15, 20 and 30 m spacings. Similarly, Youngs *et al.* (1989) water-management modelling of low-lying lands bisected with ditches demonstrates good agreement can be achieved between modelled and observed data by assuming that non steady state can be approximated with a series of steady state simulations. Leeds-Harrison (unpublished) combines Youngs *et al.* (1989) solution with Ernst-Hooghoudt theory in his 'WatMod' model. The WatMod model provides a robust yet empirical steady state water-management equation, linking hydraulic properties of the soil, water-management regime and sub-irrigation spacing with meteorological data.

3. Research rationale, scope and means of investigation

3.1. Rationale

As carbon budgets come under increasing scrutiny and water resources under increasing pressure there is a demand for greater efficiencies in land management and water use.

Over recent years agricultural research has placed greater emphasis on improving SOC stocks, whilst environmental research efforts have focussed on quantifying global carbon budgets and on determining carbon cycling in wetlands. Such research of peatlands (the largest repositories of terrestrial organic carbon) has, however, continued to focus on either intact wetlands or upland mires (Drzymulska, 2004**,** Makila and Toivonen 2004**,** Blinova *et al.* 2004, Juottonen *et al.* 2004, Takada *et al.* 2004). Comparison of recent and past soil surveys demonstrates that the considerable losses of organic carbon from terrestrial systems still occurs from low-lying sites (Richardson and Smith 1977, Burton and Hodgson 1987), where extensive drainage for agricultural reclamation has exacerbated rates of subsidence and mineralisation of the soil. Where agricultural peatland subsidence has been investigated studies have either focussed on monitoring changes in surface elevation (topography); assessing the effects of changing tillage practices (Morris *et al.*, 2004b); or the effects of mixing peat with *in-situ* mineral deposits (Andriesse, 1988); or incorporating *ex-situ* material into the peat (Cook, 1990). Other discrete pieces of research have investigated the feasibility of sub-irrigation to aid peatland ecological status (Hooker, 1991) and on the potential of ditchwater management to reduce peat subsidence **(**Hooper *et al.*, 1996 and Brandyk *et al.*, 2004). A considerable amount of research has focussed on investigating the physical and hydraulic attributes of peat soils at the micro-scale (Rycroft *et al.*, 1975 and Kennedy and Price, 2005) and the biochemistry of peat soils, studying microbial respiration **(**Inubushi *et al.*, 2003) and community structure (Borgå *et al.* 1994, Sundh *et al.* 1997). To the author's knowledge, there has been no prior programme of integrated research that has simultaneously studied the effects of land-use and water-table manipulation on both physical degradation and biochemical mineralisation of low-lying agricultural peat soils in England.

3.2. Contribution to knowledge

There is a paucity of integrated research combining the influence of soil water regime and degree of peat soil degradation on the continued physical and biochemical degradation of low-lying agricultural peat soils. Determination of water-regimes that mitigate degradation and loss of peat may assist land managers to identify water-management strategies that are appropriate to their circumstance and hence enhance their capacity to achieve sustainable peat soil use. This work intends to increase the knowledge base of the role that water-table manipulation can play in controlling the degree of physical and biochemical degradation of low-lying agricultural peatlands in England under different land-uses and at different stages of degradation.

3.3. Detailed aim

To provide a set of water regime management options that mitigates the impact of agricultural land-use on low-lying peat soil degradation.

3.4. Outline hypotheses

Having appraised previous peatland research, a number of questions were raised about the nature and intensity of low-lying peatland use and of water management regimes. This led to the following hypotheses being drawn up concerning low-lying agricultural peatland sustainability:

- Differing land-uses exert an influence on the magnitude of organic carbon loss through gaseous exchange of the greenhouse gas carbon dioxide.
- Soil water regime influences the physical and biochemical properties of peat soils, that themselves control the degree of structural degradation of peat.

- A high water table decreases change to the physical and biochemical integrity of peat soil and therefore reduces degradation and loss of that soil.
- Optimal water-management scenarios exist that can decrease peat soil degradation whilst having minimal impact on land-use.

3.5. Objectives and scope of research

To assess the effects of water-table regime on peat soil wastage, this research will carry out quantitative investigation by:

- Researching how land-use has exerted an influence on the magnitude of peat soil degradation.
- Studying the effect of soil water regime on the physical and biochemical differences in peat soils.
- Analysing the effects of water-table regime on the loss organic carbon from the soil.
- Identifying those water-table management scenarios that may reduce the impact of land-use on peat soil degradation whilst maximising its sustainability.

The results of the work aim to inform stakeholders involved in peat soil management of alternative water-management scenarios that may improve the sustainability of their resource. However, the water-management options should be treated with care, as the findings pertain to only two land-use scenarios, within specific micro-environments.

3.6. Thesis structure

This work has a remit spanning a number of scientific disciplines. To address the subject successfully the thesis is structured to consider each research discipline as follows:

Chapter 4 provides a background of the regions of interest where the low-lying peatlands are found; differentiating the regions on the basis of climate and predominant land-use. The research sites selected within each of these regions are discussed.

Chapter 5 uses topographic and soil survey to assess the current status of the identified low-lying agricultural peatlands. Such surveys demonstrate the extent of agricultural peatland degradation and loss; as expressed through changes in surface elevation (subsidence) and changes in degree of peat soil degradation. Peatland subsidence and degradation results from the combined effects of consolidation, shrinkage and mineralisation and the following chapters consider each of these aspects individually.

Chapter 6 is a micro-scale study of the physical and hydraulic properties of peat soils at different stages of degradation and under different soil moisture conditions. The influence of variable degrees of degradation and soil moisture status on a peats capacity for water storage, retention and transmission are determined. This chapter provides fundamental information about various peat's hydraulic properties that are required for the subsequent investigation of water management scenarios; through water-table modelling (chapter 8).

Chapter 7 investigates the micro-scale effects of soil moisture, temperature and nutrient amendment on the mineralisation rates of peat soils at different stages of degradation.

Chapter 8 studies the feasibility of enhanced water-table management with variously spaced sub-irrigation systems. Empirical modelling is used to study water-table fluctuation under such irrigation systems.

Chapter 9 continues the investigation of SOM mineralisation but at a larger scale. Rates of soil respiration are monitored under variable water-table management regimes in a field-scale pilot study and on large diameter soil cores. The consequence of such large-scale water management on the mineralisation of SOM is also considered from the perspective of changes in soil microbial community structure.

Chapter 10 draws the physical and biochemical findings of previous chapters together to consider whether enhanced water-table management scenarios exist that can improve the sustainability of low-lying agricultural peatlands. The consequence of present and various future climate scenarios for low-lying agricultural peatland sustainability is considered. Physical and biochemical processes are coupled through two process based models in a case study of rates of organic matter mineralisation and subsidence under different water management regimes.

Chapter 11 draws conclusions and makes recommendations concerning the capacity for such water-table management to improve low-lying agricultural peatland sustainability.

3.7. Outline methodology

To investigate the relationship between water-table management, soil moisture and carbon loss from peatlands the following strategies were employed:

3.7.1. Experimental design

The majority of observation and experimental work in this thesis has been concerned with measuring the effect of physical and biochemical soil attributes on a response variable (i.e. soil water content, hydraulic conductivity and water retention). These hydraulic parameters in turn may have altered the physical and biochemical attributes (i.e. bulk density, respiration rate). To investigate the interactions of these inter-relationships at both small- and large-scales three types of experimental technique are employed:

- <u>Retrospective studies:</u> Comparison of historical topographic and soil survey data with recent investigations allows the extent of peatland subsidence and degradation to be investigated for different land-use and water-management practices.

- Manipulative experiments: Manipulation and control of the experimental conditions is used to study whether cause and effect relationships can be demonstrated between soil water regime and peat degradation; thus allowing relationships between physical and biochemical variables to be deduced.

- Prospective studies: have aimed to extrapolate the likely experimental outcomes from the present time to some point in the future. Field-scale management of soil water content through installation of sub-irrigation and subsequent monitoring of field water-table levels in conjunction modelling theoretical water-table fluctuation enables soil water deficit to be considered with and without the use of water-management intervention. This aims to optimise sub-irrigation strategies on peatlands to minimise organic carbon losses.

3.7.2. Field studies.

The following investigations are undertaken across both of the research sites:

- Topographic surveying to assess the combined effects of consolidation, shrinkage and biochemical mineralisation on long-term subsidence.
- Soil surveying to assess the extent of deterioration of the physical structure of peat soils.
- Soil sampling for physical and biochemical analyses.
- Installation and monitoring of various replicate sub-irrigation treatments to determine the effect of spacing on field-scale water-table position.
- Installation of a monitoring point on each different sub-irrigation treatment to assess potential gains and losses of water to the 'closed system'.

3.7.3. Laboratory investigations.

Whilst field studies provide understanding of total system degradation, there are too many variables at work to analyse the effects of each on peat degradation rates. Laboratory experiments are used to simulate the various water regimes encountered in the field whilst enhancing control of soil moisture, temperature and soil nutrient status.

This facilitates analysis of the importance of peat type, soil moisture, temperature, nutrient status and soil ecology on the rate of peat degradation.

This work involved:

- Analysis of physical and hydraulic attributes of different peat types.
- Analysis of soil respiration, microbial biomass and community structure.
- Determination of peat soil SOM content, SOC content, nutrient status and soil pH.

3.7.4. Statistical analysis and data presentation

To evaluate the findings a number of different statistical methods are used:

- Descriptive statistics of discrete data sets provided the mean and standard error.
- Where direct comparison is possible between the effect of soil moisture regime and a physical or biochemical response variable the data is compared by Analysis of Variance and the probability and Least Significant Difference quoted.
- Where the number of variables is extremely large, Principal Component Analysis (PCA) is employed. Re-analysing large data sets by PCA reduces the number of variables to a manageable number of new variables. This allows the effects of different treatments to be considered using more rigorous parametric statistical methods.
- To determine whether relationships exist between physical, hydraulic and biochemical soil and water attributes, correlation (R^2) and regression analysis are employed.

4. Research region background

In the East Anglian Fenland and Somerset Moors the majority of peatlands belong to the 'Earthy Peat Soil' Group, with most of the soils having formed from fen or fen-carr (woody) peat. The sub-surface horizons range from calcareous to extremely acid. As these peatlands formed in what were estuarine environments they are frequently underlain by high pyrite content clay. Where long-term drainage exposes the Fen Clay to aeration, sulfate reducing bacteria are able to utilise the pyrite as an electron acceptor. When combined with the large sink of readily available carbon the combination can result in sulfuric horizons and ochre production.

Across both regions the parent material from which the peat formed is reported to have been very similar and therefore the selection of research sites within these areas seems appropriate. Any subsequent differentiation in physical and biochemical properties of the peat will have resulted from changes in the natural environment but anthropogenic activities, such as land-use and drainage practices, are liable to have had the greatest influence.

4.1. South-West England

According to DEFRA (2006) the South-West region covers 18.3 per cent of England's land area and has greater than 75 per cent of its land under agricultural production. DEFRA (2006) assess that of this agricultural land that by 2001 27 percent was under crops and 65 per cent was given over to grassland (this grassland figure having fallen from a high of 75 per cent in 1974, due to the expansion of arable cropping). The National Farmers Union (Nation Farmers Union, 2002) report that dairy farming accounts for 41 per cent of the grassland use, whilst extensively reared cattle and sheep account for a further 29 per cent.

Within the South-Western region (Figure 5), the Somerset Moors constitute one of the largest and richest areas of traditionally managed wet grassland and fen habitats in England, with the majority of the area being only a few metres above mean sea level.

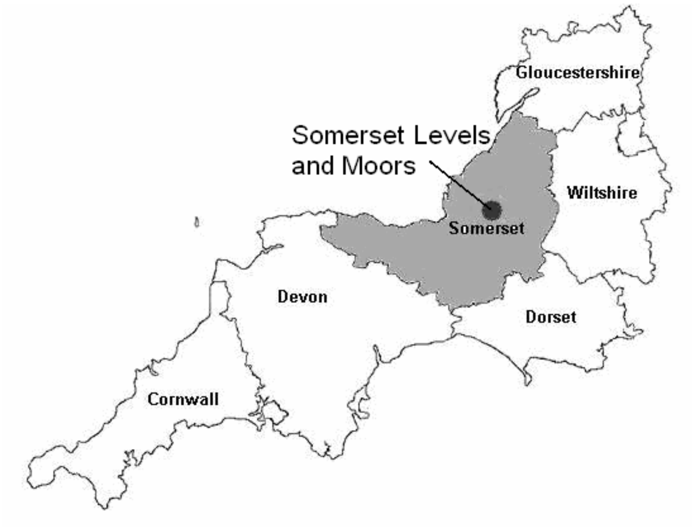


Figure 5: South-Western region, with location of Somerset Levels and Moors broadly identified.

Parts of the Somerset Levels and Moors remain prone to flooding in winter, depending on rainfall and tidal conditions. The area is therefore drained through a large network of ditches, rhynes, drains and rivers. Historical agricultural intensification and peat extraction has resulted in large areas that were once raised peat bog being substantially modified (Appendix **A.2**). There are now large areas of open water, fen and reed bed. Burton and Hodgson (1987) estimate that the Somerset Moors cover over 95 per cent (16,350 hectares) of the regional peatland resource, with peat deposits ranging from 4 to 8 m in thickness.

4.2. East Anglia

According to DEFRA (2006) the East of England region covers 14.7 per cent of England's land area and has greater than 75 per cent of its land under agricultural production. It is a predominantly low-lying and open area, ranging from the flat fens that to coastal areas that are interspersed with lakes, rivers and the associated wetlands of the Broads. DEFRA (2006) assess that by 2001 71 per cent of this land was given over to crop production and 15 per cent to grassland.

East Anglia most obviously supports intensive arable farming and horticulture and remains the largest horticultural producing region in the UK, with 41,761 hectares.

Within this region the county of Norfolk has the most intensive horticultural production system, covering 16,755 hectares, much of which lies in the Norfolk Fens (Figure 6). However, the East Midland region follows closely behind East Anglia in horticultural activity; with 37,162 hectares given over to production. The majority of this land is in the county of Lincolnshire (32,733 hectares), which lies to the North-West of Norfolk and also forms part of the Fens.

Figure 6: County of Norfolk, with location of Methwold Fen broadly identified.

4.3. Regional climate

Regional differences in environmental conditions play a significant part in soil hydrology, with climate having a strong bearing on the potential for water management on peatland sites.

4.3.1. South-West England

Climatically, the South-West of England is very varied due to significant differences in altitude (ranging from 0-120 mAOD[6]) and proximity to the sea. Generally, the pattern is one of warm winters, cool summers and relatively high rainfall. This can constrain field activities and livestock grazing periods, due to impassable ground

[6] Above Ordnance datum (mean sea level at Newlyn, Cornwall)

conditions. The UK Meteorological Office (2006) state that average long-term rainfall is 1006 mm (ranging from 614-2320 mm year-1) and average accumulated temperature is high, at 1443 ºC (but ranging from 949-1654 ºC). In the driest parts of the region (western coastal districts and lowlands in the east) there can, however, be a significant deficit below the national mean precipitation. This often leads to drought conditions during the summer and a scarcity of water resources.

4.3.2. East Anglia

Climatically, the Anglian region is influenced by its proximity to the continent. The UK Meteorological Office (2006) report that the region has a long growing season, experiences warm summers and mild winters. Compared with the national average temperature of 1352 ºC, the accumulated regional temperature of 1395 ºC is more favourable for agriculture. The region is, however, the driest part of the country, with an average annual rainfall of 600 mm. This is only two thirds of the national average of 836 mm. The low-lying fens experience an even lower annual average rainfall of only 553 mm. Droughts are therefore a regular feature of regional climate, with notable periods of drought having occurred in the early 1990s'. Such water deficits often limit ground water recharge and reduce river flows in many parts of the region.

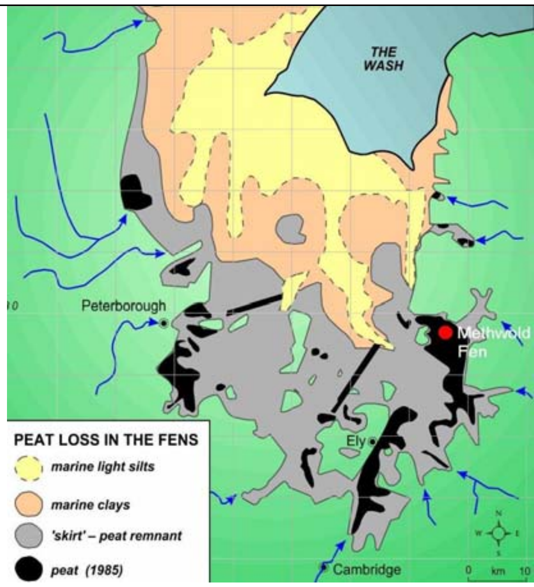
4.4. Study areas

Within each region the specific peatland sites selected are representative of the dominant peatland-use within that region. Both research areas have water management strategies in place but they differ significantly according to the land use.

In the South-West a grassland where fen peat underlies a thin alluvium was chosen in southern part of the Somerset Levels and Moors (Figure 7a); at West Sedgemoor (51°01.00'N 2°56.15'W).

In the East Anglian region a site of exposed fen peat under intensive arable farming was selected in the Norfolk Fenlands (Figure 7b); at Methwold Fen (52°31.52'N 0°28.16'E).

a: West Sedgemoor (South-West)



b: Methwold Fen (East Anglia)

Figure 7: Lowland peat regions (b: after Burton and Hodgson, 1987)

4.4.1. West Sedgemoor

West Sedgemoor forms part of the River Parrett catchment; draining into the Severn Estuary (Figure 8).

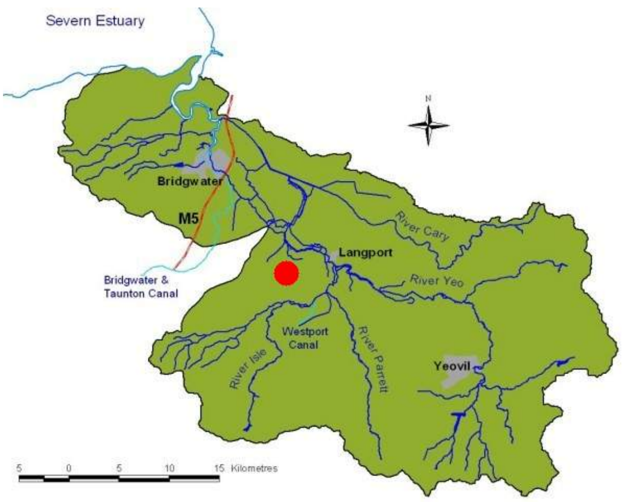
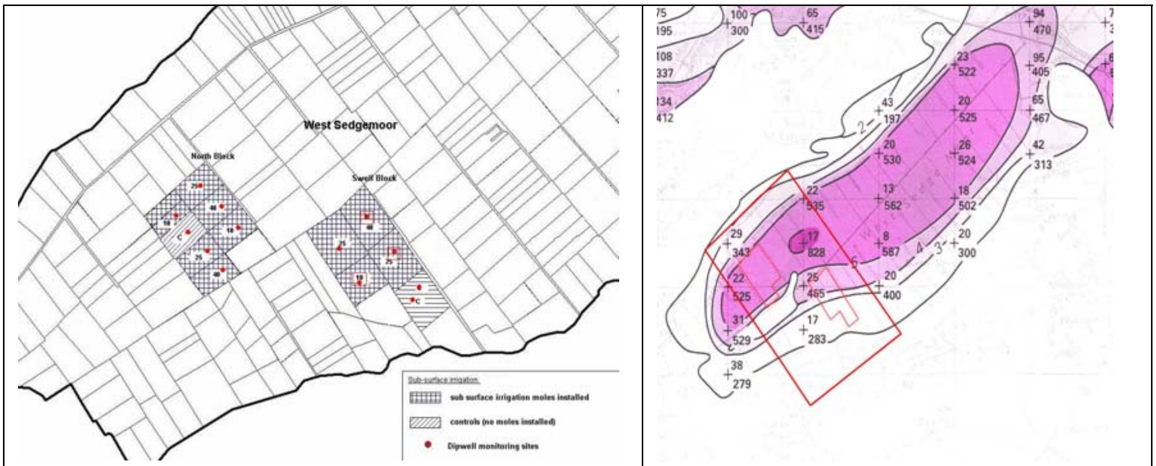


Figure 8: River Parrett catchment, with the location of West Sedgemoor highlighted.

The West Sedgemoor site covers approximately 1035 hectares whilst the 12 research fields span 37 hectares (Figure 9a). Peat is reported to range from 3 to 8 m in thickness (Figure 9b).



a. Research fields | b. West Sedgemoor peat thickness

Figure 9: West Sedgemoor research fields and peat thickness (after Cope and Coleborne, 1981)

The research site belongs to the Royal Society for the Protection of Birds (RSPB). Across the research site a Raised Water Level Management Strategy (RWLA) has been adopted as part of an Environmentally Sensitive Area (ESA) management plan. The water-management strategy, defined as Tier 3 management, requires that the ditchwater levels are maintained at mean field level throughout the winter and early spring months, whilst during the summer and autumn months the water level is dropped to 0.3 m below mean field level.

4.4.2. Methwold Fen

Methwold Fen is an extensive peatland lying in the north-eastern part of the East Anglian Fens, to the South of Kings Lynn and to the North East of Ely. It forms part of the River Wissey catchment (Figure 10).

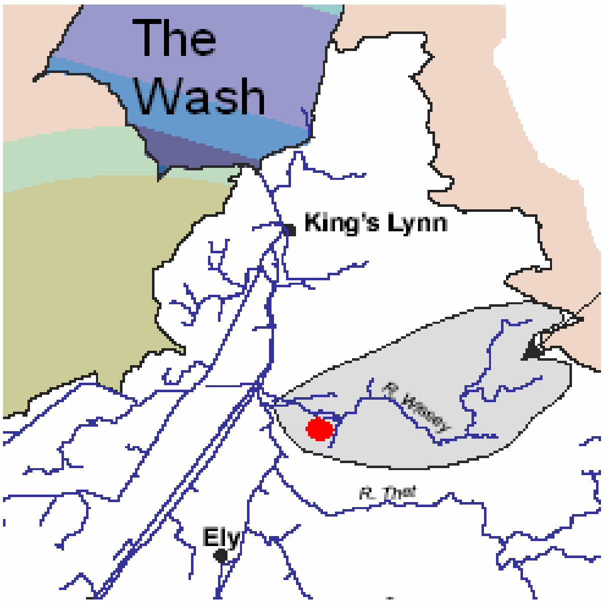


Figure 10: The river Wissey catchment with the research area at Methwold Fen highlighted (red marker).

The Environment Agency (2004) assessed the drainage systems feeding into the River Wissey as heavily modified waters. This suggests that the waterways bisecting Methwold Fen affect the physical and chemical composition of water flowing into it.

Methwold Fen covers an area of approximately 1300 hectares, with the research farm covering a significant proportion of the total (Figure 11a). The peat is generally 1-2 m thick but exceeds 5 m thickness locally (Burton and Hodgson, 1987). The research station is on a site of 3 hectares (Figure 11b).

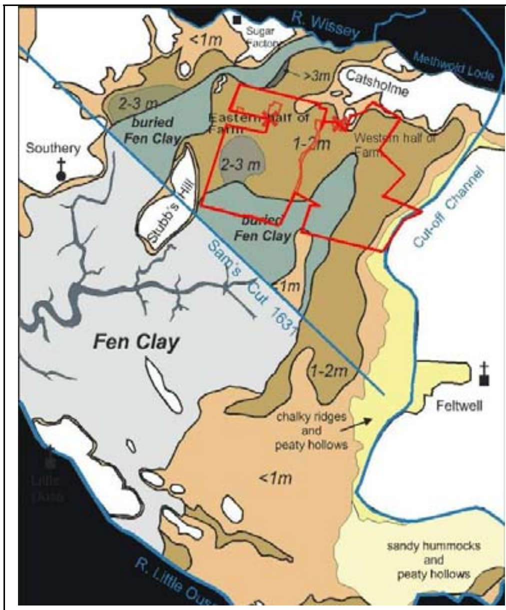
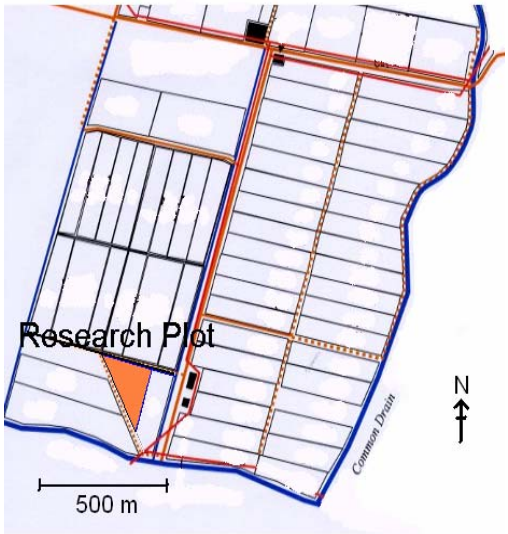
	
a. Methwold Fen peat type and thickness (after Burton (unpublished).	b. Schematic of research site location

Figure 11: Methwold Fen peat thickness with an outline of the combined Eastern and Western halves of the research farm (11a) after Burton and Hodgson (1987). Also, an enlargement of the Western half of research farm, with the research field highlighted in orange (11b).

The water-management strategy is complex; with 4 different water levels being maintained across the farm. The water supply is pumped from the Internal Drainage Board (IDB) channels bisecting the farm into the farm's own system of ditches, where control structures are used to manipulate particular ditchwater levels during the spring to autumn months. During the winter months the pumps are switched off to aid complete drainage of the site.

5. Topographic and soil surveys of lowland agricultural peatlands.

5.1. Introduction

Peat subsidence has several serious consequences. Falling surface elevations require a corresponding lowering of water-table level to maintain the status quo, otherwise inundation and flooding is likely to occur. Similarly, man-made structures (roads, buildings and bridges) may become unstable due to variable subsidence rates. From an agricultural perspective, the rooting systems of perennial crops are liable to be exposed, with top-heavy crops becoming partially up-rooted.

Inter-seasonal topographic surveying identifies short-term fluctuations in surface elevation due to swelling and shrinkage of the soil as the soil moisture changes. Longer-term monitoring, on decadal time-scales, allows degradation and loss of peatlands due to physical and biochemical erosion to be investigated.

One approach to monitoring such subsidence that has been adopted by a number of researchers (Schothorst 1977, van den Akker, unpublished) relies on the installation and monitoring of ‘winged’ gauges in individual soil horizons against a fixed reference point of known elevation. Whilst such a method provides useful data over the long-term, over the shorter-term the invasive nature of winged gauge installation leads to structural damage of the peat and could misinform the user about subsidence rates. The more traditional method of topographic survey, when combined with soil surveying, offers an alternative short-term means of investigating the combined effect of land-use and water-management practices on the degradation and loss of this resource.

The West Sedgemoor peatland in Somerset has received considerable attention over recent decades because it is highly valued for both ecological and archaeological reasons. English Nature (1997) suggests the peats of West Sedgemoor have accumulated over the last 10,000 years. The Ross and Heathwaite (1987) soil survey of the area identified three key stages to this peatland development. Initially, wet freshwater reed-swamp conditions predominated in base rich ground waters. This was succeeded by a fen carr environment in slightly drier conditions followed by a return to wetter conditions and the development of base rich sedge and grass which forms the basis of the present day landscape. Brown *et al.* (2003) reported that extrapolated age-depth curves of these peats indicated no loss of peat in the upper 2 m of the profile but that some shrinkage had occurred in the upper 0.2 m. Brown *et al.* (2003) also reported that the peat profile was capped by 9 cm thick organic silty-clay and the underlying peat was moderately humified herbaceous peat with small wood fragments in the base horizons. However, neither Ross and Heathwaite (1987) nor Brown *et al.* (2003) expanded on the extent of degradation of individual peat horizons that have a bearing on water-table management at West Sedgemoor. Coles and Orme (1983) discuss the humified condition of the peat but it was the Cope and Coleborne (1981) investigation that provided a more comprehensive survey of the overlying alluvium, the peat type and thickness of deposit. Cope and Coleborne (1981) reported that the peat averaged 5.5 m thick (with shallow edges of 2.79 m and deeper hollows up to 8.28 m but generally ranging from 5.22–5.87 m in the middle of the moor) and that the upper 0.5 m of peat was extensively humified. Though the Cope and Coleborne (1981) investigation was more detailed it was on a large-scale and the resultant map publication of peat type was based on botanical composition of the peat and not the degree of individual peat horizon degradation.

At Methwold Fen the soil inventory by the England and Wales Soil Survey (Burton, unpublished soil survey 1982/3) provides one of a few detailed sources of information about the state of peats in the Anglian region. Being under intensive agricultural management the area appears to have been of much less ecological or archaeological interest than West Sedgemoor; though other peatlands in the Anglian region are now receiving renewed interest (*e.g.* Wicken Fen, Cambridgeshire). Fortunately, the Burton (unpublished soil survey 1982/3) detailed record of peat degradation throughout the soil profile enabled a direct comparison against the soil survey undertaken during this work. This facilitated an investigation of peat degradation over several decades. An important part of Burton's (unpublished soil survey 1982/3) work included an investigation of soil pH. In drained peatlands underlain by Fen Clay such studies are especially important. Burton and Hodgson (1987) demonstrated that the high sulfate content of Fen Clay, when combined with a readily available source of carbon, can lead to the production of acid sulfate soils that contain sulfuric sub-surface horizons with pH 2. Such reactions can lead to the formation of ochre (Thorburn and Trafford, 1976), which can clog sub-irrigation systems, foul waterways and limit the potential yield of surface crops.

From a water-management perspective, the type of soil survey undertaken by Burton (unpublished soil survey 1982/3) and in this study provides useful information for the sub-irrigation and drainage engineer. Knowledge of peat texture and bulk density (porosity) may enhance understanding of soil hydraulic properties, whilst knowledge of peat thickness and of underlying impermeable boundaries provides boundary conditions essential to hydrological modelling and the design of appropriate irrigation / drainage schemes.

5.2. Aim

To quantify the historical consequence of different land-use and water-management practices on the rate of subsidence and degradation of lowland agricultural peatlands.

5.3. Objectives

- To calculate the degree of peatland subsidence under different land-uses and water-management practices.
- To investigate how land-use and water-management practices have degraded different peat soil horizons.

5.4. Methods

5.4.1. Topographic survey

During the summer and winter periods of 2003 and 2004 topographic surveys were carried out across the research sites at West Sedgemoor and Methwold Fen. Though a number of methods exist for topographic surveying ‘differential levelling’ was employed in this work using a Leica NA824 automatic leveller (accurate to +/- 2 mm) fitted to a Wild GST20 tripod, in conjunction with a telescopic surveying staff. Differences in surface elevation were established between points of interest by recording back-sights, foresights and intermediate sights between points on a standard surveying proforma, and fixing all points relative to a Permanent Benchmark (BM) of known height (Figure 12).

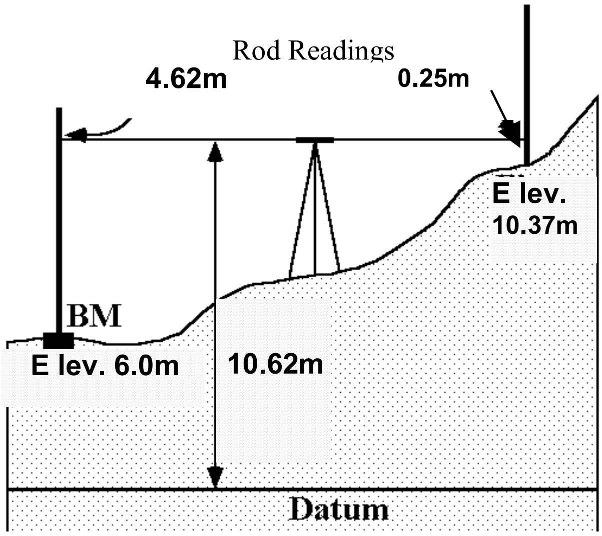


Figure 12: Differential levelling of changes in surface elevation.

Where some historical topographic surveys had previously reduced such surface elevation data to a standardised Benchmark of 100 mAOD[7] the data was converted back to absolute elevation above mean sea level (relative to ordnance datum Newlyn). In this form the data was comparable with recordings of water-table levels and also allowed a comparison of regional differences in surface elevation (considered in chapter 8).

At West Sedgemoor topographic survey was undertaken over the area covering 12 research fields, at 250 m intervals. A more detailed survey was also undertaken within each research field to facilitate subsequent water-table investigations (chapter 8). Separate surveys were undertaken on three occasions (at different times of year) to identify seasonal and annual changes in surface elevation. The surveys were compared against historical survey data provided by the land manager (Paget-Wilkes,

[7] mAOD = metres Above Ordnance Datum, Newlyn.

unpublished). All survey data was fixed relative to the Ordnance Survey Benchmark at Underhill Farm (ST359244), which is recorded as 11.32 mAoD. At the end of surveying a final check was made against this benchmark; indicating that all surveying was accurate to +/- 1 cm.

At Methwold Fen the size of the research area (9 km^2) precluded topographic survey of the entire peatland. Instead, triplicate fields previously categorized by Burton (unpublished soil survey of 1982/3) as; 'fibrous peat underlain by Fen Clay'; 'fibrous peat with no underlying Fen Clay' and, 'humified peat not underlain by Fen Clay', were resurveyed. This topographic survey data was compared against historical data provided by the land manager (Martin Hammond, unpublished).

Given the precision farming practices employed at Methwold Fen, previous surveys required a minimum of 12 survey points per hectare. Topographic surveying during this study was similarly intensive, with survey points established at 40 m intervals along 50 m spaced transects running perpendicular to the edge of each field under investigation. All survey work was fixed relative to the Ordnance Survey Benchmark at Severall's Bridge (TL679956), which is recorded as 2.80 mAoD. To assess the accuracy of surveying work a final check was made against this benchmark; indicating that all survey work was accurate to +/- 1 cm.

5.4.2. Soil survey

Whilst the WRB classification system aims to create a unifying system of peat soil classification many countries still maintain their own classification system. Such is the case in England and Wales. The classification system according to 'The Soil Survey of England and Wales (Avery, 1980), was therefore the sole system used in this work and followed the procedure prescribed by Hodgson (1997).

All soil surveying was undertaken using standard 3 cm diameter, 1.5 m length, Dutch and Gouge augers with extension poles. All findings were recorded on a standard soil survey proforma; logging details of grid reference, date, slope, land-use, horizon thickness, state of humification (von Post, 1924), hue and colour (Munsell Colour Company, 1954), stone abundance, presence of Calcium Carbonate and pH. The information was subsequently subject to statistical analysis and comparison against historical data (where available).

At West Sedgemoor the small size of the research area and limited access meant a detailed survey was undertaken at 250 m intervals (based on ordnance survey grids superimposed over the 37 hectare area of interest). The reduced number of available grid survey points and the requirement for soil profile data on specific research fields[8] meant additional soil profiles were catalogued adjacent to each point of interest. The soil survey inventoried the degree of degradation through the upper metre of peat[9] according to the von Post scale (von Post, 1924). Beyond one metre depth the soil survey was restricted to recording the thickness of peat deposit to the underlying mineral deposit / impermeable boundary.

At Methwold Fen the survey replicated a comprehensive lowland peat survey undertaken 21 years previously by Burton (Burton, unpublished soil survey of 1982/3). A 500 m interval survey grid was superimposed over the 9 km^2 of the research area. Triplicate boreholes were then augered to the underlying mineral horizon at each grid point. Though the thickness of peat to the impermeable layer was recorded, only the upper metre of peat profile was described[9] according to the von Post scale (von Post, 1924). Each of the triplicate boreholes was within a 10-m radius of the original survey point inventoried by Burton in 1982/3. This triplicate borehole analysis was undertaken to enhance subsequent statistical analysis.

5.4.3. Soil pH

Determination of soil pH requires soil samples to be placed in solution (Buck *et al.*, 2002). The solvent used varies and can be water, 1 Molar Potassium Chloride or 0.01 Molar Calcium Chloride. However, water cannot remove hydrogen ions from electron exchange sites in the soil and is seen by many as a poor solvent for soils with varying or high salt content. pH results obtained using water as a solvent are therefore prone

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[8] Soil surveying was also undertaken adjacent to dipwells installed in each research field. These survey points were selected to aid the study of sub-irrigation spacing on water-table management (Chapter 8).

[9] This was the section of soil profile believed most susceptible to aeration and hence biochemical mineralisation. The assumption was based on seasonal variations in water-table discussed in chapter 8.6.2.1.

to inter-annual fluctuations and interference from fertilizer applications. Potassium chloride displaces hydrogen ions from the soil's cation exchange sites and minimises differences in the soil's salt content. The results therefore tend to be slightly lower than other methods and enhance the accuracy of pH determination. Calcium Chloride solvent is an intermediate method between the water or potassium chloride methods, masking small differences in the soil's salt content. Burton (unpublished soil survey 1982/3) employed this latter method to determine soil pH in his survey of 1982/3. The latter method was therefore employed in this study to enable comparison against Burton's 1982/3 study.

- During the survey of both research areas samples were collected from each horizon down to a depth of 1.0 m.
- Within 24 hours the field moist samples were sieved (<2 mm) and 5 grams of soil weighed into labelled plastic bags.
- Each soil sample was amended with 25 ml of 0.1 Molar Calcium Chloride solution.
- Each sample was then shaken for 20 minutes at room temperature (25 °C) and allowed to settle for a further 5 minutes before pH determination.
- An Oxford Labs 3020 pH meter was calibrated by two point calibration (pH 4 and pH7) and the pH probe subsequently placed in each sample until the pH value equilibrated. A record was taken of soil source, horizon, type and pH.
- The pH meter was recalibrated after every 10 samples using the aforementioned 2 point calibration.
- Similar to Burton (unpublished soil survey of 1982/3), the effects of long-term aeration on the peat's acid potential was analysed by leaving samples to stand at room temperature (25 °C) with the top of the plastic bag left open for a period of 3 months. After 3 months the soil pH was measured again, using the same method.

5.5. Results

5.5.1. Topographic survey

Table 1 demonstrates the change in surface elevation (due to subsidence and/or swelling) over the last 10-15 years (relative to ordnance datum at Newlyn) for both research sites.

West Sedgemoor	1993 height (mAoD)	2003 height (mAoD)
	4.93 (48,0.02)	5.04 (48, 0.01)
Methwold Fen	**1991 height (mAoD)**	**2004 height (mAoD)**
	-0.66 (117, 0.03)	-0.85 (117, 0.04)

Table 1: Two sets of topographic survey data for each of West Sedgemoor and Methwold Fen (one historical and the other recent). Data demonstrates the rise in surface elevation over a period of 10 years at West Sedgemoor and the fall in surface elevation over a period of 13 years at Methwold Fen. All values are means (sample size and standard error of the mean are given in parentheses).

It can be seen that the West Sedgemoor Basin has a surface elevation above Ordnance Datum (Newlyn) whilst the Methwold Fen site lies below it. It also appears that at the West Sedgemoor research site there has been an increase in surface elevation whilst at Methwold Fen there has been a fall in elevation.

The findings demonstrate that across the Methwold Fen area surface elevation poses additional water-management constraints, as any form of land drainage requires water to be pumped uphill to the river systems that drain the wider catchment area. The comparison of topographic survey data also suggests that with the passage of time Methwold Fen is becoming more reliant on the complex water-management system in place as the fall in surface elevation suggests the area is becoming increasingly susceptible to flooding.

At West Sedgemoor, a comparison of mean surface elevation between the two plots, North Block and Swell Block (Figure 9a) containing the 12 research fields suggests that North Block, in the middle of the moor, is approximately 0.2 m lower than Swell Block (at the edge of the moor). However, the variations in surface elevation between individual spot heights within each field also demonstrates that variability is large and that there is no overall difference in elevation between individual research fields between the two plots (Table 19, appendix D.1). Comparison of present day against historical elevation data across the RWLA (Table 18, appendix D.1) indicates there has been an annual increase in surface elevation of 1.0 cm year^{-1} over the 10 year period between 1993 to 2003 ($p<0.001$). In contrast, Brown *et al.* (2003) reported there had been little or no change in peat thickness over recent years. However, a small-scale inter-annual study of surface elevation changes between the winter of 2003 and the winter of 2004 (Table 20, appendix D.1) suggests a small decrease in elevation of 0.1 cm from 2003 to 2004, though the change was not statistically significant ($p=0.67$). The inter-seasonal surveys, between summer 2003 and winter 2004 (N=13, SE=1.3) indicate a highly significant ($p<0.001$) increase in surface elevation of 4.3 cm (Table 21, appendix D.1). This demonstrates the importance of inter-seasonal shrinkage and swelling when considering long-term subsidence.

At Methwold Fen the comparison of this study's 2004 survey against survey data from 1991 indicates a mean annual decrease in surface elevation of 1.4 cm year^{-1} (N=117, SE=0.19) over a 13 year period. Due to the considerable variability in rates of subsidence (Table 22, appendix D.1) the survey data was reanalysed according to the predominant peat type and underlying boundary conditions. Figure 13 depicts long-term average falls in surface elevation according to predominant peat type and/or underlying mineral deposit (after Burton's 1982/3 unpublished soil survey).

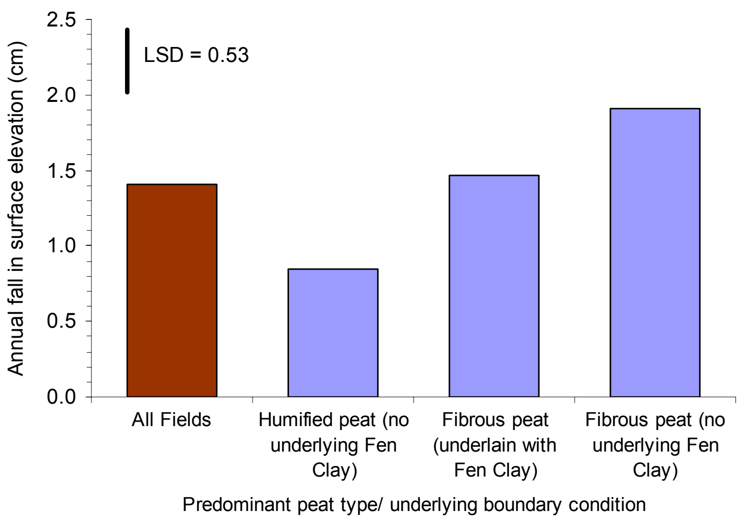
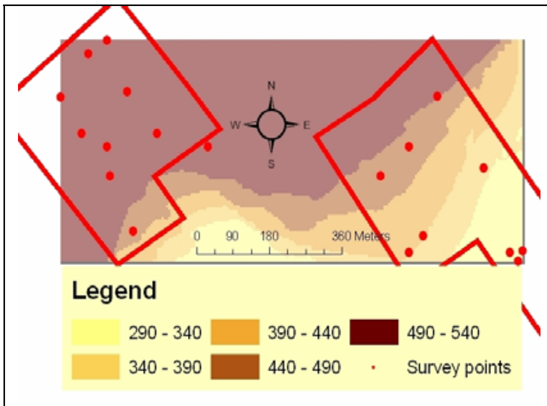


Figure 13: Methwold Fen fall in surface elevation over a 13 year period (error bar denotes LSD at 5% CI).

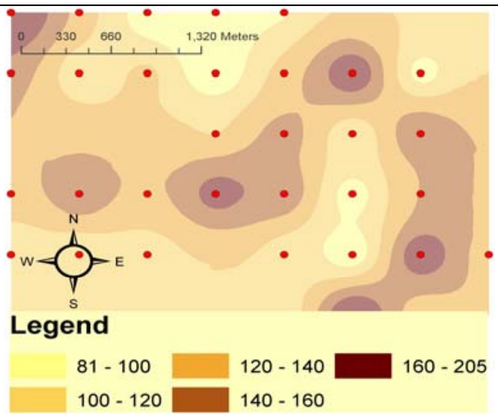
Analysis of variance (Table 23, appendix D.1) indicates that those fields of predominantly fibrous peat and no underlying Fen Clay have a significantly higher mean annual subsidence rate of 1.9 cm $year^{-1}$ than the humified peat without an underlying impermeable layer ($p<0.001$). The humified peats without an underlying impermeable layer have a mean annual subsidence rate of 0.9 cm $year^{-1}$. However, fibrous peat areas that are underlain by Fen Clay have an intermediate rate of subsidence averaging 1.5 cm $year^{-1}$. All recorded subsidence rates are, though, lower than those reported by Hutchinson (1980) and French and Pryor (1993) who estimated 2-4 cm $year^{-1}$ subsidence rates across the Fens.

5.5.2. Soil survey

Figure 14 depicts current peat thickness at both West Sedgemoor and Methwold Fen. Contour maps were created using simple Geostatistical kriging and interpolation between soil survey points (ESRI ArcGIS). These representations demonstrate that there are considerable differences in peat deposits between the research sites. Though the general peat thicknesses reported here do agree with findings of Cope and Coleborne (1981) and Burton and Hodgson (1987) the accuracy of interpolation between data points is dependent on the variability in thickness between such points and the resulting maps should be used with caution.



a. West Sedgemoor



b. Methwold Fen

Figure 14: Geostatistically interpolated schematics of peat thickness at: 'a' West Sedgemoor and 'b' Methwold Fen. Peat deposits range from 0.8 to 5.4 m in thickness. Contour lines represent 0.5 m increments in peat deposit thickness for West Sedgemoor peats and 0.25 m increments for Methwold Fen.

At West Sedgemoor the peat thickness averages 5.25 m (6, 1.25); decreasing in thickness toward the edge of the West Sedgemoor basin (Figure 14 a). The findings demonstrate the considerable variability in peat thickness. The results are also in general agreement with the mean and the range of values reported by both Cope and Coleborne (1981) and Burton (unpublished soil survey 1982/3). However, the lack of detailed historical survey data precluded a more detailed investigation of changes in peat thickness over recent decades. Burton (unpublished) also undertook a small-scale deep soil survey in 2004 that affirmed the findings.

At Methwold Fen this study determined an average peat thickness of 1.28 m (33, 0.06) in 2004. This is in contrast to the historical average peat thickness reported in 1982/3 which, based on a detailed re-analysis of the Burton data (unpublished soil survey 1982/3) suggests an average historical thickness of 1.52 m (32, 0.06). This latter re-analysis of Burton (unpublished soil survey 1982/3) findings also agrees with Burton and Hodgson (1987). The findings therefore demonstrate that there has been an average subsidence rate of 1.2 cm year^{-1} over the last 21 years. A more detailed analysis of rates of change in thickness of different peat deposits suggests that areas previously described as predominantly fibrous in 1982/3 (Burton, unpublished soil survey 1982/3) have not changed at a greater rate than those previously described as humified ($p<0.91$). The findings are in contrast to the surface elevation data reported here. The results are, though, similar to the more general report by Price (2003); that long-term losses of intensively managed agricultural peatlands range from 1-5 cm year^{-1}.

The soil surveys enabled a generic soil profile to be constructed of the upper 1 metre of peat for both research areas (Figure 15). This provides the foundation of the investigation into water-table management discussed in chapter 8.

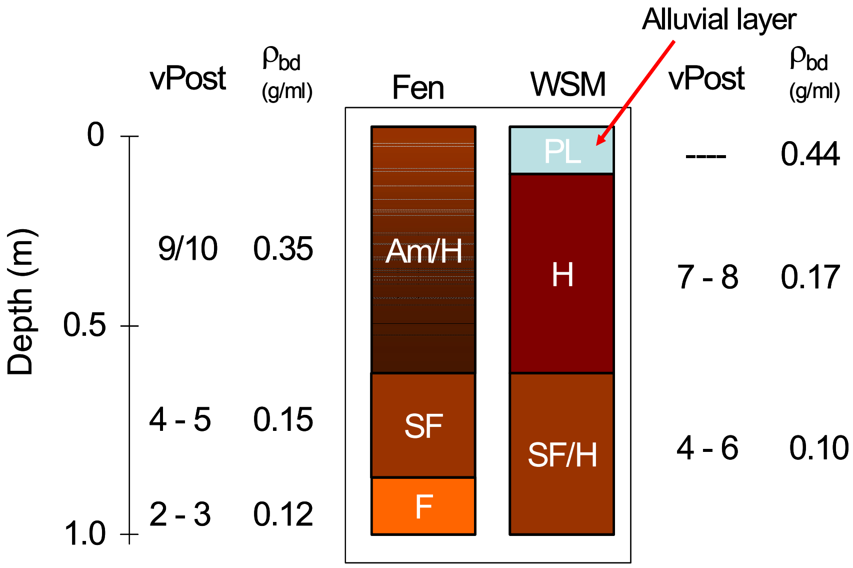


Figure 15: A generic soil profile for West Sedgemoor (WSM) and Methwold Fen (Fen). (vPost= von Post value (von Post, 1924) and PL=Peaty Loam; H=Humified; SF=Semi-Fibrous; and, F=Fibrous according to the modified von Post scale (Burton and Hodgson, 1987).

At West Sedgemoor the survey affirmed that the peat on the research plots was capped with an organic mineral soil layer classified in this work as a peaty loam. Some authors (Brown *et al.* 2003) describe this surface horizon as organic silty clay; however, analysis of SOC content (Table 29, Appendix E.2) suggests it is equally valid to classify it as a peaty loam (21.3 per cent). The underlying peat horizons are generally humified to a depth of 0.6 m, which is in general agreement with Brown *et al*. (2003) and Cope and Coleborne (1981). Between 0.6 and 1.0 m depth the peat is less degraded, being classified in this work as semi-fibrous peat.

At Methwold Fen soil survey indicated that surface horizons were consistently very highly degraded amorphous / humified peat to a depth of 0.75 m. Below this depth the peat was consistently less degraded than surface horizons. The generic peat profile (Figure 15) incorporates spatial variations in the predominance of less degraded peat types below 0.74 m depth. Though the thickness of peat has changed since the previous soil survey of 1982/83 a comparison of this work against the 1982/83 soil survey (Burton, unpublished soil survey 1982/3) indicates that the relative proportion of amorphous/humified peat to the combined proportion of fibrous and semi-fibrous peat horizons in the upper metre of the soil profile has decreased.

5.5.3. Soil pH

Soil pH was determined for each soil horizon from each of the survey points at both research sites. The non uniform rate of peat degradation between each survey point precluded presentation of all data, which is presented in Figure 16 as the composite of pH averages across 3 depth ranges: 0 – 0.33 m, 0.33-0.67 m and 0.67-1.0 m from these surveys.

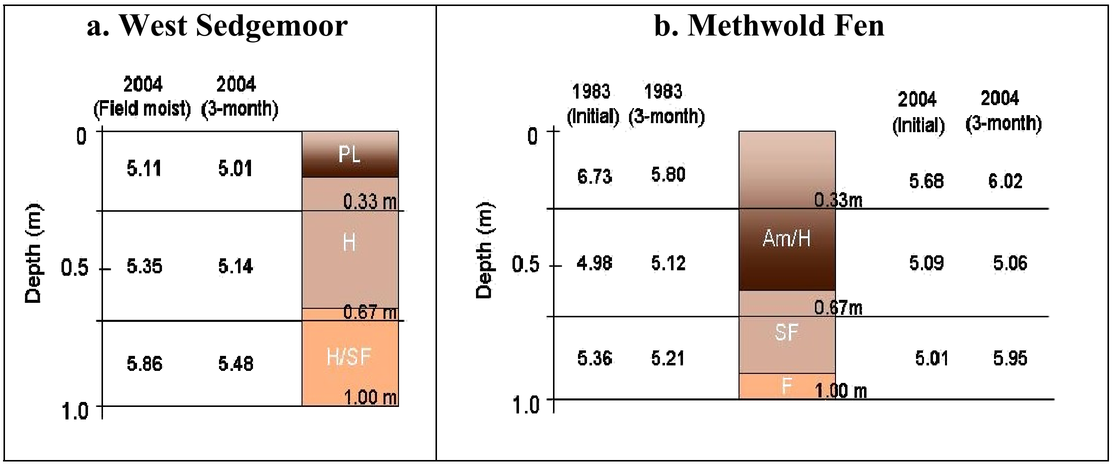


Figure 16: Soil pH determined at field moist and after 3-months areation for Peats from Methwold Fen and West Sedgemoor.

At West Sedgemoor pH across all soil horizons down to a depth of 1.0 m ranges from 4.09 to 6.81 (39, 0.11). The pH was generally more acid in the surface horizon than at depth. After a 3 month period of aeration the pH had changed very little in West Sedgemoor peats; ranging from 4.26 to 6.83 (39, 0.10).

Methwold Fen peats displayed a greater spatial range of initial pH; ranging from 3.99 to 6.57 (65, 0.07) and after 3-months aeration pH ranged from 3.17 to 7.17 (65, 0.11). pH was generally more acid in sub-surface horizons than in surface horizons. Below 1.0 m depth, where Fen Clay exists, spot samples suggest there are also potential acid sulfate peat horizons with pH down to 2.99. The soil pH in the upper metre of peat has not changed significantly since the last soil survey in 1982/3 (when pH ranged from 3.6 to 7.7 (66, 0.11)). Also, re-analysis of data from 1983 suggests peats did not have the same propensity for acidification after 3-months aeration in 1983 as they do now (range from 3.70 – 7.55 (66, 0.11)).

5.6. Discussion

At West Sedgemoor the minor long-term increase in surface elevation over the RWLA may be due to the slow re-saturation of the peat soil rather than peat accumulation. It should be borne in mind that levelling equipment in this work is accurate to 0.2 cm and hence the 2003 surveys are accurate to +/-1.2 cm. There is a considerable seasonal change in surface elevation which implies that some degree of non-permanent consolidation results. This appears to coincide with the seasonal change in water-table depth from summer to winter. Though the findings are in contrast with Brown *et al.* (2003) the results of this work are confined to a much smaller geographic area than the Brown *et al.* (2003) survey and are also only applicable to the RWLA. The soil survey corroborates the findings of previous workers; that the upper 0.6 m of peat is highly humified. Previous reports did not, however, publish detail of the more fibrous peat horizons below this level. The results indicate the peats are generally slightly acidic and that surface horizons have slightly lower pH than sub-surface horizons. The lower pH of surface horizons and the considerable thickness of the peat profile therefore suggest that the surface peats may be detached from sub-surface mineral deposits and that the peatland could now be characterised as ombrotrophic.

At Methwold Fen the peatland has continued to subside over the last 21 years but at a slower rate than that reported by Hutchinson (1980). It also appears that in areas where fibrous peat predominates that the rate of subsidence is greater. But, where such fibrous peats are underlain by Fen Clay the rate of subsidence is lower. The lowest rate of subsidence occurs in areas where humified peat predominates. It seems apparent that the predominant peat type is a strong determinant of the rate of subsidence. The soil survey data indicates a greater proportion of fibrous material exists now, relative to 1982/3, in the upper metre of the soil profile. One might expect the proportion of humified peat to have increased as biochemical degradation occurs, however, it appears that the more fibrous peat is being exposed from deeper horizons as the humified peat is mineralized and, possibly, that this fibrous peat is mineralizing at a relatively slower rate than the surface horizons. This suggests the fibrous peat may belong to a more recalcitrant carbon pool. It also seems probable that the more fibrous peat has a greater propensity for physical consolidation, whilst the amorphous peat, which is liable to have collapsed to such an extent that any further physical consolidation is minimal, may be mineralizing at a greater rate. The findings also indicate that where Fen Clay exists either the Fen Clay is acting as an impermeable boundary and keeping these peats more saturated or the lower pH associated with Fen Clay is reducing the capacity for microbes to mineralize SOM. It also seems that in places some sub-surface peat horizons have greater acid sulfate potential. This is only likely to become apparent at the surface as the peat deposit continues to mineralise.

5.7. Conclusions

There are inherent errors in mapping topographic and soil survey data. Soil surveying is limited by the use of a semi-quantitative measure of the degree of degradation of peat, whilst geostatistical mapping of peat thickness relies on interpolation of soil attributes between survey points. The generic soil profiles described in this work should therefore be treated with caution, as they are composites of various peat profiles. However, topographic and soil survey of the peatlands at West Sedgemoor and Methwold Fen affirm that these two areas are experiencing considerably different rates of subsidence and degradation of the soil profile. One displays marginal increases in elevation whilst the other demonstrates considerable subsidence and a decrease in the thickness of peat deposit. Where the peat deposits are quite shallow and underlain by Fen Clay there is an increased potential of acid sulfate horizons that could damage crop yield or lead to abandonment when crops can no longer grow.

Each peatland has adopted distinct water-management practices and it is hypothesised it is the water-management regime that accounts for such differences in the subsidence and degradation encountered. On the intensively farmed peatland the water table is held at -0.5 m below mean field level during the summer and deeply drained during the winter to facilitate land maintenance activities; to a depth greater than -1.5 m. Conversely, on the conservation peatland the water table is held continually high, only being dropped marginally during the summer months to allow low stocking density grazing.

To study whether different peats at different stages of degradation respond differently to the water-management regime requires an investigation of the physical properties and biochemical nature of a range of peats under a range of water-management scenarios. The following chapters address each of these facets in turn to determine whether subsidence and peat degradation can be minimised by adapting existing water-management strategies.

6. The consequence of drainage on the physical and hydraulic properties of peat soils

6.1. Introduction

Any form of peat soil water-management intervention relies on the capacity of the soil to store, transmit and retain water. Knowledge of the basic hydraulic properties of a soil facilitates appropriate water-management planning and intervention. However, seasonal changes in the water-table management practices of low-lying agricultural peatlands have consequences for the physical properties that dictate such water storage capacity, retention and transmission. This provides a basis to investigate the physical and hydraulic properties of such soils further.

For mineral soils an empirical relationship exists between the water storage (porosity) of the soil and the range and relative proportion of a soils particle sizes, or soil texture (Warrick, 2002). Other attributes, such as particle packing density and aggregate structure, also influence the range of soil pore sizes and their inter-connectivity. The sum of these physical characteristics defines a soil's capacity for storage, retention and transmission of water. In peat soils, though, the dearth of such discrete soil particles precludes the use of such conventional soil particle-size analysis in explaining the soils hydraulic properties. Indeed, as discussed in chapter 2, textural analysis of peat soils relies primarily on the quantification of the soils organic matter content. The other attributes of packing density, soil structure and the inter-connectivity of soil pores do, however, remain useful concepts for differentiating between the hydraulic properties of peat soils at different stages of degradation.

A fluctuating water-table exposes different soil horizons to changing pressure potentials and hence to changes in soil moisture content in the vadose zone. Though such soil-moisture deficits subject mineral and peat soils alike to changing physical and biochemical stresses, only the capacity of mineral soils to transmit and retain water under such conditions have been shown to vary according to soil texture. Peat soils also exhibit different hydraulic properties under changing moisture deficits, but also exhibit extreme shrinkage responses to such moisture deficit. It may be surmised that, just like mineral soils, the extent of peat water retention capacity will vary according to packing density, structural integrity and inter-connectivity of soil pores. In addition, though peats appear to conform to the constancy of volume concept (rigid soil theory) under long-term, non-stressed, saturated soil moisture conditions, their shrinkage characteristics, water retention capacity and transmission under stressed conditions varies according to degree of degradation. To investigate the hydraulic properties of peat soils therefore requires an appreciation of their physical properties (texture, bulk and particle densities and shrinkage characteristics), their degree of degradation (packing density, structural integrity and inter-connectivity of soil pores), but most importantly, the soils' capacity to store, transmit and retain water.

6.2. Contribution to knowledge

Current knowledge of the relationship between the degree of degradation of peat soils and their capacity for storage, retention and transmission of water remains poor (Holden and Burt, 2003). This study intends to contribute to the body of soil physical knowledge concerning the relationships that exist between peat hydraulic properties and degree of peat degradation; by identifying the principal factors controlling variable water storage and flow phenomena.

6.3. Aim

To determine the effect of degradation status and drainage on the physical and hydraulic properties of some selected peat soils, with a view to informing sustainable water management.

6.4. Objectives

- To investigate variously degraded peat soils capacity for water storage, retention and hydraulic conductivity under saturated conditions and changing pressure potentials.

- To identify the relationships between physical and hydraulic attributes of a range of degraded peat soils in order to identify the key soil attributes determining water storage, retention and transmission.

6.5. Outline methods.

The investigation of the hydraulic properties of peats under saturated soil moisture conditions considers only unconfined fully swollen saturated peat and is based on rigid soil concepts (*i.e.* that a soils unit volume remains constant under unstressed saturated moisture conditions). For unsaturated soil moisture conditions the effect of shrinkage and swelling is quantified (Appendix C).

6.5.1. Textural analysis

In mineral soil science there is a strong correlation between soil structure, texture and porosity (Monier *et al*., 1973). Indeed, the addition of organic matter enhances the structure and improves the total porosity of mineral soils (Anderson *et al.* 1990, Schjoning *et al.* 1994). To determine whether the texture of peat soils (SOM content), as specified by Burton and Hodgson (1987) and the degree of degradation on the von Post scale (von Post, 1924 - appendix B.2) has a similar effect on water storage and retention, it was initially necessary to establish whether a relationship exists between the von Post score of degradation and the SOM content of each peat.

Soil survey work (Chapter 5) identified key locations where a range of discrete peat types (of varying degradation) were located. Samples of these peats were initially ranked according to the modified von Post scale (Burton and Hodgson, 1987) and subsequently refined according to the fuller von Post scale (von Post, 1924). To confirm the samples were indeed peats (Histosols) a textural analysis of the SOM content was undertaken on triplicate samples of each soil type, in accordance with British Standard (1990) loss-on-ignition method (Appendix C.1).

6.5.2. Measurement of the potential water storage capacity and flow of water under saturated soil moisture conditions.

6.5.2.1. Maximum porosity (ϕ)

The maximum porosity of triplicate samples of each peat type was determined according to British Standards (1990); where the dry bulk density (based on volume at saturation) and particle density enables calculation of maximum porosity according to the relationship:

$$\varphi = 1 - \frac{\rho_{dbd}}{\rho_{pd}}$$

Equation 2: Maximum porosity.

where maximum porosity.(ϕ) is in $cm^3\ cm^{-3}$, dry bulk density (ρ_{dbd}) is in g cm^{-3} and particle density (ρ_{pd}) is in g cm^{-3}.

Previously reported dry bulk density values of peat soils range from 0.1 g cm^{-3} to 0.39 g cm^{-3} (Andriesse 1974, Schwarzel *et al.* 2002). Given the variability of reported values new dry bulk density values were required for the peat types used in this work (Table 38, Appendix E.6).

Triplicate samples were collected in soil rings of known volume and saturated for 2 days. The samples were then trimmed to the known volume of the soil rings and the dry weight of each sample determined after oven drying to constant weight (105 °C for 48 hours). The relationship between dry weight and initial sample volume was calculated using the relationship:

$$\rho_{dbd} = \frac{M_{solids}}{V_{total}}$$

Equation 3: Dry bulk density.

where dry bulk density. (ρ_{dbd}) is in g cm^{-3}, mass of solids (Msolids) is in g and initial volume of soil (Vtotal) is in cm^3.

Peat particle densities have been reported to range from 1.1 – 1.55 g cm^{-3} (Verdonck *et al.* 1983, Brady and Weil 1999, Jury and Horton 2004), but without stating the method of analysis. In this work the particle density was determined on triplicate samples using the British Standard 7755 (1998) pycnometer method. However, the method employed a non-polar organic fluid (hexane) in preference to water; to ensure complete sample saturation (Appendix C.3).

The particle density of the peat was defined as the dry mass of soil divided by the volume of the soil particles:

$$\rho_{pd} = \frac{M_{solids}}{V_{solids}}$$

Equation 4: Soil particle density.

where soil particle density. (ρ_{pd}) is in g cm^{-3}, Mass of solids (M_{solids}) is in g and volume of solids (V_{solids}) is in cm^3.

6.5.2.2. Saturated hydraulic conductivity

The rate of flow during saturated soil moisture conditions was determined using Darcy's equation, which defines the hydraulic conductivity of a soil as being proportional to the velocity of flow through a unit length of soil experiencing a known pressure potential gradient:

$$Q = KA\frac{\Delta h}{L}$$

Equation 5: saturated hydraulic conductivity.

where saturated hydraulic conductivity (K) is in m s^{-1}, the rate of flow is in m^3 s^{-1}, the cross sectional area of sample (A) is in metres, the length of sample (L) is in metres and the hydraulic gradient (Δh) is in metres.

Based on reports that hydraulic conductivity values in peat soils are low to intermediate the falling head permeameter method was adopted in this work. Field measurement of hydraulic conductivity by borehole development and slug removal testing was investigated but deemed inappropriate for identifying individual peat horizons hydraulic conductivity. The falling head permeameter method allowed the heterogeneity and anisotropy of discrete peat soil horizons to be studies and also minimised sample disturbance (as the method precluded repacking).

Sampling was in triplicate for each peat type through both vertical and horizontal sections. Each sample was subjected to three different hydraulic pressure head gradients to ensure the calculated mean hydraulic conductivity was representative of variable pressure head gradients likely to occur under field conditions.

6.5.3. Storage, flow and retention of water under variable unsaturated soil moisture conditions.

6.5.3.1. Shrinkage characteristics under increasing pressure potentials.

Variable shrinkage under increasing pressure potentials brings into question the validity of rigid soil theory for determining the hydraulic properties of peat soils under moisture stress (increased pressure potential). The effect of peat shrinkage characteristics on hydraulic properties of the soil may have significant consequences for aerobic microbial mineralisation and degradation of organic matter (Chapter 7), as changes in the ratio of soil pore space to soil moisture may mean that the shrinking peat matrix remains relatively saturated.

The shrinkage characteristics of the different peat soils considered two models of conceptual shrinkage. The 3-phase shrinkage model presented by Bronswijk and Evers-Vermeer (1990), though based on clay soil findings, appeared pertinent to shrinkage of all none rigid soils. This model described shrinkage as ‘normal’ when the bulk soil volume decrease equals the water lost from the soil system; ‘residual’, when the decrease in bulk soil volume continues but to a lesser extent than water loss; and ‘zero shrinkage’ when the soil particles have reached their greatest packing density and further water extraction has no effect on aggregate volume. Hendriks (2004) 3-phase conceptual model was developed specifically for peat soils, with shrinkage phases redefined as ‘near normal’ when soil volume reduction is close to water loss and the soil remains saturated (because there is little or no air-entry); ‘sub-normal’, when soil moisture loss exceeds volume reduction and air entry occurs in larger pores and finally 'super-normal' when volume reduction far exceeds moisture loss, because water leaves the soils micro-pores and the 'skeletal' structure of the peat collapses.

The dimensions of the triplicate samples of each peat type were recorded simultaneously with determination of each peats water retention characteristics (section 6.5.3.2). Where void and moisture ratios to solids were calculated for each peat sample at each pressure potential as:

$$\text{Void Ratio} = \frac{\text{Volume of Pores}}{\text{Volume of Solids}}$$

Equation 6: Void ratio.
where the volume of pores and solids are both in cm^3, and

$$\text{Moisture Ratio} = \frac{\text{Volume of Moisture}}{\text{Volume of Solids}}$$

Equation 7: Moisture ratio.
where the volume of moisture and solids are all in cm^3.

These void and moisture ratios allowed the shrinkage characteristic curves of individual peats to be constructed, analysed and compared against each other and against the conceptual models of Bronswijk and Evers-Vermeer (1990) and of Hendriks (2004).

6.5.3.2. Water retention characteristics under increasing pressure potentials.

When assessing the ability of the peat to retain moisture (water retention characteristics) triplicate samples of each peat type were pre-saturated for a period of two days. Subsequently, a range of successively increasing pressure potentials were applied to each sample; each for a period of two weeks. At the end of each two week period samples were weighed and measured to determine water retention and degree of volumetric change. Calculation of soil moisture content at each pressure potential followed classic water retention analysis and initially discounted the variable shrinkage of different peats, as results were based on the standardised sample volume at saturation. In all, eleven pressure potentials were applied to each sample, with the upper most pressure potential applied at -150 m (permanent wilting point), after which the samples were oven dried and the final weight and dimensions measured and recorded.

The van Genuchten (1980) closed form equation (Equation 8) identifies several key parameters of the soil water retention curve that allow calculation of other soil hydraulic parameters. The van Genuchten closed form equation (van Genuchten, 1980) was therefore fitted to the observed water retention characteristics of the different peats by a process of iteration:

$$\theta = \frac{(\theta_s - \theta_r)}{(1 + (\alpha h)^n)^m} + \theta_r$$

Equation 8: van Genuchten closed form equation for calculating soil moisture content at a given pressure potential (in metres).

where α and n are fitting parameters obtained by fitting to experimental data by a process of iteration, with $m = 1 - (1/n)$ and $0 < m < 1$).

6.5.3.3. Dominant pore size and drainable porosity

Previous work on mineral soils (Warrick, 2002) has demonstrated that pore size and pore space connectivity in the form of micro-joints are equally as important as total porosity of a soil in determining the movement of water through the soil. In peat soils the pressure potential at which the maximum rate of water loss occurs is a point of considerable interest for peatland water management, as different soil management scenarios may modify the relative proportion of rapidly draining pores in peats at different stages of degradation. White (1985) found that the volume fraction of pores ≥ 30 µm and the continuity of these pores had a strong effect on water movement. A number of other authors also report that greater capillary flow results in the vadose zone when such smaller pores exert a stronger pull on the residual water (Price and Whitehead, 2002; Schlotzhauer and Price, 1999; and Schlotzhauer, 1999).

During tensioning of the replicate peat samples the water retention characteristics provided basic information on the rate of water loss with pressure potential. Determining the first order derivative of van Genuchten (1980) closed form equation

(Equation 9) enables numerical solution of the maximum rate of change in soil moisture content (θ).

$$\frac{\partial\theta}{\partial h} = -(\theta_s - \theta_{res})\left[\frac{1}{1+(\alpha h)^n}\right]^m \left[\frac{m}{1+(\alpha h)^n}\right]\left[\frac{(\alpha h)^n n}{h}\right]$$

Equation 9: First order derivative of van Genuchten equation
where δθ is the change in soil moisture (cm^3 cm^{-3}) , δh is the change in pressure potential (m), θ_{sat} and θ_{res} are the soil moisture contents at saturation and at 150 m pressure potential (cm^3 cm^{-3}), α and n and m are the fitting parameters from the van Genuchten closed form equation for water retention characteristics.

To determine the dominant pore size a version of the La Place equation (White, 1985) was employed (Equation 10). By dividing the pressure potential at which the rate of change in soil moisture is greatest by the maximal rate of change in pressure potential (δθ/δh) the dominant pore size in the soil can be calculated.

$$\Delta \mathrm{h} = \frac{2\sigma \cos\gamma}{\mathrm{r}}$$

Equation 10: The capillary model of soil water
where the relationship between the radius of theoretically inter-connecting capillary tubes in soil and potential for capillary rise are determined. Δh is the capillary rise (Length units), r is the radius of the capillary tube (Length units), γ is the contact angle (in radians) and σ is the interfacial surface tension.

Warrick (2002) simplifies Equation 10 by combining the known constants and typical values for γ and σ and rearranging the equation in the form:

$$\Delta h = \frac{14.84}{r}$$ which approximates to: $$d \approx \frac{30}{\Delta h}$$

Equation 11: Simplified determination of dominant pore size.
where Δh is the change in pressure potential (m), r is capillary radius in μm and d is pore diameter.

The pressure potential at the point of maximum rate of change in soil moisture content also allows the difference in moisture content between saturation and the *capillary* *storage capacity* (Neilsen and Luckner, 1989) to be determined. This value is generally considered a more effective indicator of the pore space involved in flow than total porosity. The capillary storage capacity was therefore calculated for each peat type.

6.5.3.4. Unsaturated hydraulic conductivity under increasing pressure potentials.

As a water-table falls the movement of water through the vadose zone becomes restricted to flow over the surface particulate material (unsaturated hydraulic conductivity) with both capillary rise and rates of evapo-transpiration leading to predominantly vertical movement of water. The rate of change in hydraulic conductivity has been considered by both experiment and by mathematical solution (Gardner 1958**,** Mualem 1976, Wind 1968, and van Genuchten 1980). In this work the van Genuchten (1980) closed form analytical equation for unsaturated flow (Equation 12) was used to determine unsaturated hydraulic conductivity:

$$K(\theta) = K_{sat}\left(\frac{(\theta-\theta_r)}{\theta_s-\theta_r}\right)^{0.5}\left[1-\left(1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{1/m}\right)^m\right]^2$$

Equation 12: The van Genuchten (1980) solution to the Mualem (1976) equation for unsaturated hydraulic conductivity.

where the unsaturated hydraulic conductivity K(θ) at a given pressure potential is in m d^{-1}, the saturated vertical hydraulic conductivity (Ksat) is in m d^{-1}, the soil moisture content at a given pressure potential (θ) is in cm^3 cm^{-3}, the soil moisture at saturation (θ_s) and at -150 m pressure potential (θ_r) are in cm^3 cm^{-3} and n and m are dimensionless van Genuchten (1980) parameters.

Quantifying such flow aids understanding of soil moisture losses due to evaporation through the soil surface as a water-table recedes because the water-table depth will determine whether the rate of vertical water movement limits a soils capacity to replenish soil moisture lost to evaporation. This is of considerable importance when modelling water-table movement and is considered again in chapter 8.

6.6. Results

Table 2 provides a summary of key parameters observed by direct measurement in this work. More complex data sets such as water retention, shrinkage characteristics and unsaturated hydraulic conductivity, which vary with pressure potential, are cross-referenced, in the appropriate sections, to the appendices.

There appear to be noticeable differences in the physical properties of the different peat types both within and between research sites. It is believed that these differences result from a combination of water regime and physical stress experienced by each of the various peats under investigation. The more detailed analyses that follow aim to highlight where significant variations do exist and to offer explanation for such differences and their importance with respect to peatland water management.

Source	Soil Type	Depth of sample collection (m)	Von Post ranking	Organic Matter Content (%)	Dry Bulk Density (g cm^{-3})	Particle Density (g cm^{-3})	Total Porosity (cm^3 cm^{-3})	Horizontal Saturated hydraulic conductivity (m d^{-1})	Vertical Saturated hydraulic conductivity (m d^{-1})
WSM	Peaty Loam	0 – 0.15	----	39.0	0.44	1.57	0.72	1.51	0.24
WSM	Humified peat	0.35 – 050	8	60.1	0.17	1.33	0.87	1.55	0.14
WSM	Semi-Fibrous peat	0.85 – 1.00	6	69.3	0.09	1.24	0.92	2.30	1.10
MF	Amorphous peat	0 – 0.15	10	67.3	0.35	1.37	0.80	0.27	0.22
MF	Semi-Fibrous peat	0.35 – 050	5	80.1	0.15	1.19	0.87	2.12	0.25
MF	Fibrous peat	0.85 – 1.00	2.5	80.5	0.12	1.10	0.86	2.95	0.43

Table 2: Mean physical and hydraulic parameter values for a range of peat types from West Sedgemoor and Methwold Fen.

A correlation matrix at Table 79 (appendix E.12) also gives details of the interaction between these physical and hydraulic parameters.

6.6.1. Texture

Mineral soils generally contain 5-10 per cent SOM whilst peat soils require a minimum 35 per cent of SOM to be classified as such. The different peats are ranked according to the modified and full von Post scale (given in parentheses) as follows:

- West Sedgemoor: Peaty loam, humified peat (8) and semi-fibrous peat (6).
- Methwold Fen: Amorphous peat (10), semi-fibrous peat (5) and fibrous peat (2.5).

The SOM content for each peat type is given in Table 26 and Table 27 (appendix E.1). The relationship between SOM and von Post value is depicted in Figure 17.

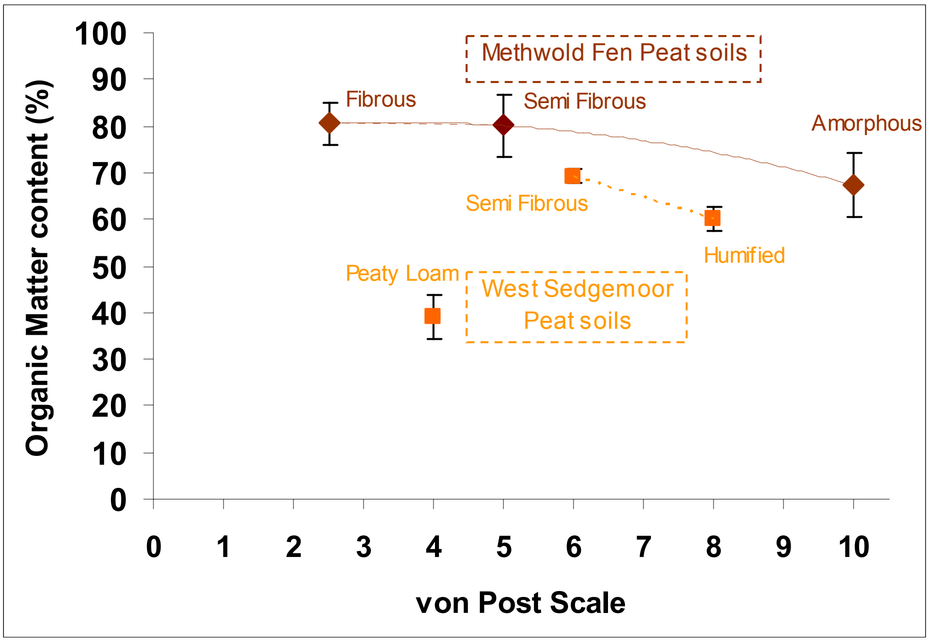


Figure 17: Relationship between modified von Post classification and organic matter content (error bars denote 95% CI).

Though peats are similarly ranked according to the modified von Post scale there are distinct differences in their SOM content. The surface layer of soil at West Sedgemoor (peaty loam) has lower organic matter content and high ash content (Table 33, appendix E.4). According to Burton and Hodgson (1987) this suggests that the surface horizon should be considered as an 'organic soil' rather than a true peat soil. For West Sedgemoor peats an analysis of variance (Table 26, appendix E.1) indicates that there is a significant decrease in SOM content with increasing degree of degradation (LSD 4.16 and $p<0.001$). Equally, for Methwold Fen peats an analysis of variance (Table 27, appendix E.1) indicates a significant decrease in SOM content between fibrous and amorphous peats (LSD 8.45 and $p<0.003$). However this latter analysis also suggests there is no significant difference in the SOM content between the fibrous and semi-fibrous peats or between semi-fibrous and amorphous peat. A statistical comparison of the SOM of similarly ranked (modified von post scale) peats from both research sites (Table 28, appendix E.1) indicates that the amorphous and semi-fibrous peats from Methwold Fen have significantly higher SOM, respectively, than the West Sedgemoor humified and semi-fibrous peats (LSD 4.72, location $p=0.003$ and soil type $p<0.001$).

6.6.2. Water storage capacity and hydraulic conductivity under saturated soil moisture conditions.

6.6.2.1. Maximum porosity (Φ), SOM content, dry bulk density and particle density.

Mineral soils generally have total porosity values ranging from 30-60 per cent but there are extremes outside this range (Bear, 1988). Previous work has shown that the total porosities of peat samples under saturated conditions are generally much higher than mineral soils, with Vedby (1984) reporting humified peats with total porosity around 75 per cent (by volume) and fibrous peats with up to 97 per cent total porosity (by volume). The peats studied in this work have total porosities ranging from 70-90 per cent (Figure 18), which is marginally lower than the findings of other workers (Boelter 1969 and Vedby 1984).

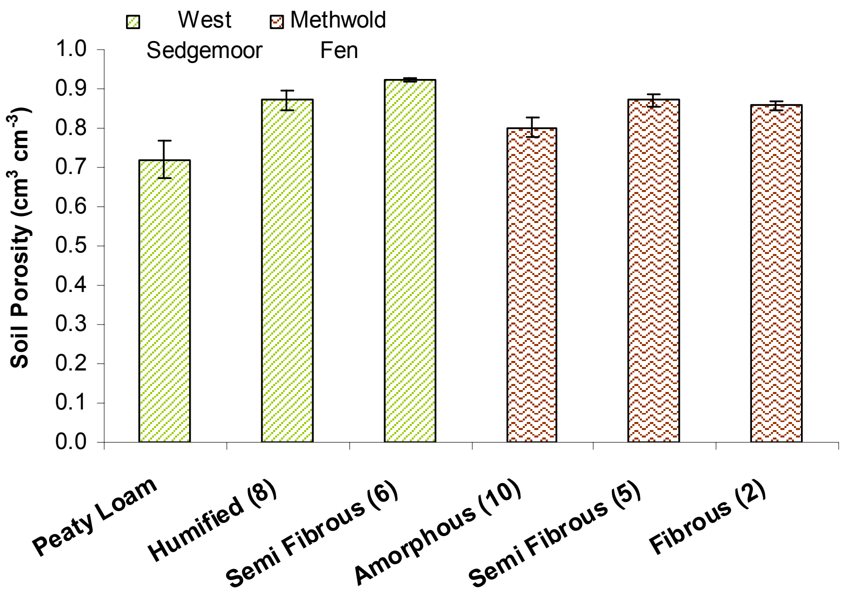
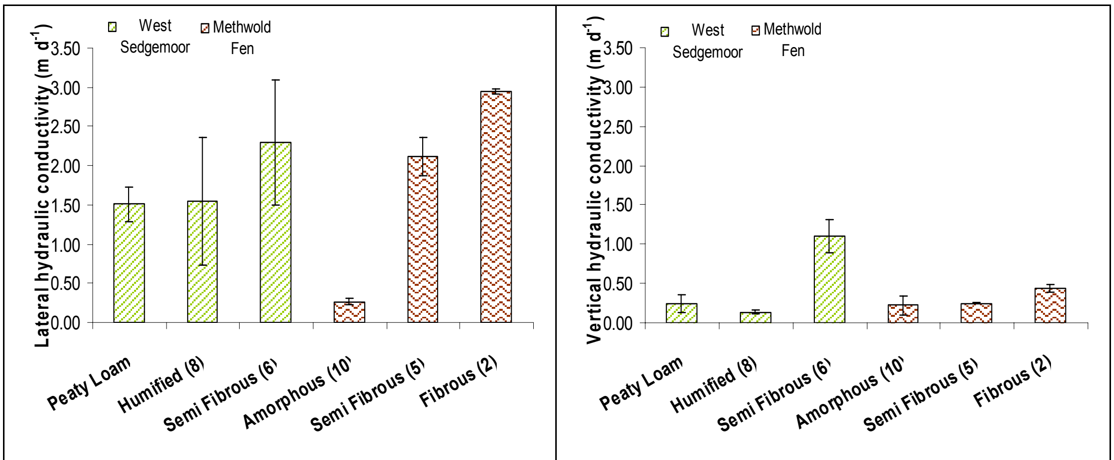


Figure 18: Total porosity (cm^3 cm^{-3}) for 3 peat types from West Sedgemoor and Methwold Fen. (error bars denote 95% CI).

The results (Table 41 and Table 42, appendix E.7) suggest a general decrease in the maximum porosity with increasing degree of humification for peats from individual research sites. Analysis of variance of maximum porosity between the peats of West Sedgemoor (Table 41, appendix E.7) indicates a significant decrease in maximum porosity from semi-fibrous to humified states (LSD 0.03 and $p<0.001$). For Methwold Fen peats the analysis of variance (Table 42, appendix E.7) indicates only the amorphous peat has significantly lower maximum porosity (LSD 0.02 and $p<0.001$) than either the semi-fibrous or fibrous peats. There is also a significant decrease in maximum porosity between similarly ranked peats from both research sites (Table 43, appendix E.7), with the amorphous and semi-fibrous peats from Methwold fen having respectively lower maximum porosity than the humified and semi-fibrous peats from West Sedgemoor (LSD: 0.02, $p<0.001$ between locations and $p<0.001$ between soil types).

6.6.2.2. Saturated hydraulic conductivity

Peat soils are generally reported to have hydraulic conductivity values ranging from 2.96×10^{-4} to 4.32 m d^{-1} (Holden and Burt, 2003) whilst mineral soil hydraulic conductivity is reported to range from 0.014 to 5.05 m d^{-1} (Rawls *et al.* 1982**,** Brakensiek and Rawls 1992). In this work lateral hydraulic conductivity receives greater analytical attention than vertical hydraulic conductivity[10], as lateral hydraulic is reportedly the most significant contributor to water movement below the water table and is generally several times greater than vertical hydraulic conductivity (Beckwith *et al*., 2003). Figure 19 demonstrates that the peat soils investigated in this work have saturated hydraulic conductivity values ranging from 0.2 - 3.2 m d^{-1} (Table 68 to Table 72, appendix E.11), with individual peats from both research sites exhibiting a considerable decrease in hydraulic conductivity between horizontal and vertical planes, respectively, of the same peat type. There are, however, exceptions. The highly degraded amorphous peat from Methwold Fen has a similar hydraulic conductivity value through both planes of flow. Also, the high variability in lateral and vertical hydraulic conductivity of semi-fibrous peat from West Sedgemoor prevents any conclusion being drawn about differences in flow between planes.



a: Lateral hydraulic conductivity. b: Vertical hydraulic conductivity.

Figure 19: Saturated hydraulic conductivity (m d^{-1}) for West Sedgemoor and Methwold Fen peats. Figure 19a shows lateral hydraulic conductivity and Figure 19b shows vertical hydraulic conductivity (error bars denote 95% CI).

The mean lateral hydraulic conductivities of West Sedgemoor peats suggest a decrease with increasing humification. Analysis of variance between peat types (Table 70, appendix E.11) shows there is a significant increase in lateral hydraulic conductivity from surface peaty loam to sub-surface semi-fibrous peat ($p<0.001$) but that there is too much variation in the data (LSD 0.46) to state whether lateral hydraulic conductivity is determined by the degree of degradation in the sub-surface true peats. A similar analysis of variance in lateral hydraulic conductivity between

[10] Vertical hydraulic conductivity becomes of greater importance for water-table modelling purposes that is addressed in greater details in chapter 8

different peat types from Methwold Fen (Table 73, appendix E.11) indicates a very clear decrease in lateral hydraulic conductivity with increasing degree of humification (LSD 0.13 and $p < 0.001$).

A comparison between similarly ranked peats[11] (modified von Post scale) from both research sites (Table 74, appendix E.11) indicates that the lateral hydraulic conductivity of amorphous peat from Methwold Fen is significantly lower than the lateral hydraulic conductivity of humified peat from West Sedgemoor (and $p<0.001$). The large variance in hydraulic conductivity (LSD 'soil type and location' 0.54) for the West Sedgemoor peats precluded any statistical significance being attached to differences in lateral hydraulic conductivities of semi-fibrous peats from the different research sites, though visual inspection suggests they are of similar magnitude.

6.6.3. Hydraulic properties under increasing pressure potentials.

6.6.3.1. Shrinkage

As increasing pressure potentials decrease the soil moisture content, different peats exhibit varying degrees of shrinkage. Figure 20 illustrates the extent of such shrinkage on a range of peats from Methwold Fen. Table 49 (appendix E.9) reports that amorphous peats may lose up to 37 per cent volume after oven drying whilst fibrous peats can lose up to 74 per cent volume after oven drying.

[11] Making the assumption that the amorphous peat from Methwold Fen is similarly degraded to humified peat from West Sedgemoor and that the semi-fibrous peats from both research sites are also similar.

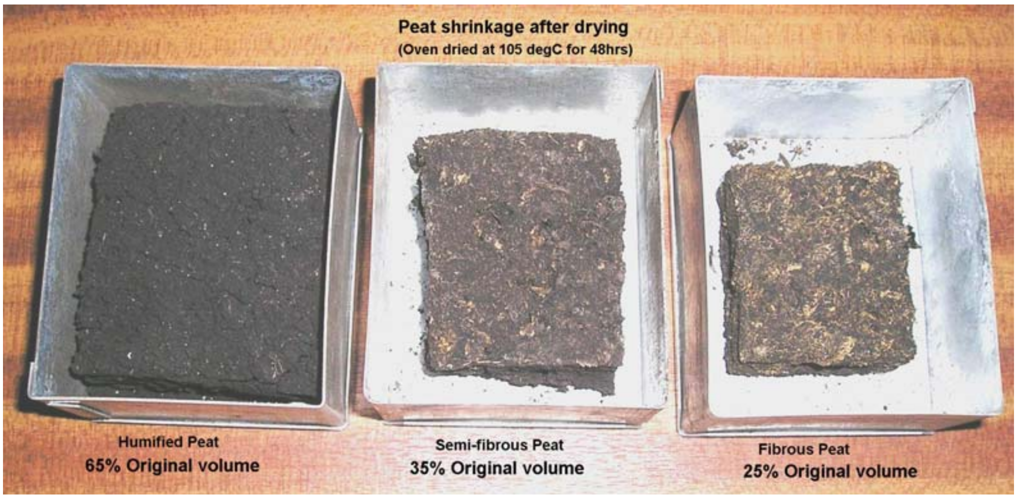


Figure 20: Shrinkage of 3 different peat types from Methwold Fen.

To interpret the relationship between shrinkage (loss of void space) and moisture content across a range of pressure potentials both the quantity of remaining voids and of soil moisture at each pressure potential are assessed relative to the absolute volume of solids in the peat. Data is summarised in Table 50 and Table 53 (appendix E.9) and provide the basis for the standard shrinkage characteristics depicted in Figure 21 for Methwold Fen peats and in Figure 22 for West Sedgemoor peats. In both shrinkage characteristic curves it can be seen that all peat samples display considerably greater shrinkage potential relative to the conceptual clay shrinkage characteristic given by Bronswijk and Evers Vermeer (1990). Also, none of the peats investigated in this work behave like the conceptual peat shrinkage characteristic reported by Hendriks (2004). Importantly, the Bronswijk-Evers-Vermeer (1990) conceptual clay shrinkage characteristics describe an immediate shrinkage response to decreasing soil moisture (as the clay initially follows the 1:1 saturation line). None of the peat soils conform to such 'Type I' normal shrinkage (*i.e.* they did not follow the 1:1 saturation line). In all peat samples the initial decrease in the moisture ratio without a change in void ratio suggests that the air entry point in these peats occurs quite rapidly after drainage commences. This immediate fall in the moisture ratio without a concurrent decrease in the void ratio needs to be considered in conjunction with the water retention characteristic data in section 6.6.3.2; where air entry appears to occur at less than -0.2 m pressure potential for all peats from both research sites.

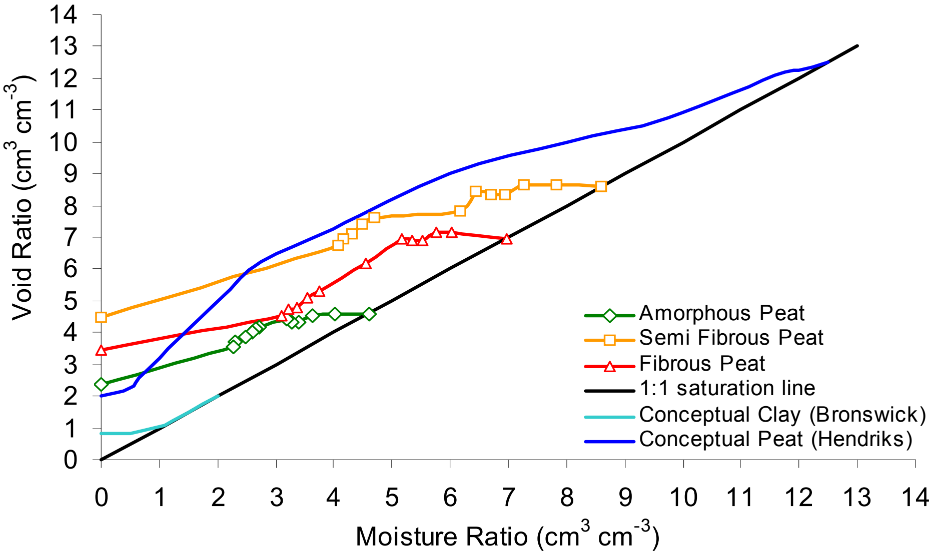


Figure 21: Mean shrinkage characteristics for Methwold Fen peats (void ratio is the ratio of voids to solids and moisture ratio is the ratio of remaining water to solids).

Analysis of variance of differences in the void ratios of different Methwold Fen peats at all pressure potentials (Table 51, appendix E.9) indicates the void ratio remains significantly greater in the more fibrous peats than in the amorphous peat at most tensions ($p<0.001$). There is no linear relationship between the degree of degradation and the void ratio; the semi-fibrous peat has a greater total void ratio at all tensions than the fibrous peat. This may be due to the different depths from which these peats were excavated. The more fibrous peat came from greater depth and is liable to have experienced greater over-burden, and hence consolidation of macropores.

At all pressure potentials, analysis of variance (Table 52, appendix E.9) also indicates that the more fibrous peats have a significantly higher moisture ratio than amorphous peat ($p<0.001$). The amorphous peat shows the smallest overall decrease in moisture ratio and the semi-fibrous peat shows a greater decrease between saturation and oven-dried states than the fibrous peat. For all Methwold Fen peats the general relationship between moisture ratio and void ratio is explained by Equation 13. Analysis of this relationship suggests that a change in moisture ratio accounts for 76.9 per cent of the change in void ratio (Table 59, appendix E.9).

$$VR = 0.872MR + 2.15$$

Equation 13: The relationship between void ratio (VR) and moisture ratio (MR) for Methwold Fen peats.

The peats soils from West Sedgemoor again have far greater moisture and void ratios (Figure 22), relative to Bronswijk and Evers-Vermeer's (1990) conceptual clay soil shrinkage characteristic. When consideration is given to the peat's bulk density it is readily apparent that these peats have a considerably greater potential for shrinkage. This is not surprising; given that clay soils have a much larger proportion of solids in the soil matrix than peats. The small shrinkage potential of the peaty loam soil concurs with this finding; exhibiting rapid change from Bronswijk–Evers-Vermeer Type I 'Normal' shrinkage to Type III 'zero shrinkage', relative to the two true peats (accounted for by the higher bulk density and ash content of the peaty loam). However, neither the humified or semi-fibrous peat conforms to the idealised shrinkage characteristic reported by Hendriks (2004) either. It is noteworthy that Hendriks (2004) also reported the same level of variability in the shrinkage characteristics of his peats as was experienced by Bronswijk – Evers-Vermeer (1990) in their work on clays. The Hendriks (2004) model nevertheless does provide a benchmark of the stages of an idealised peats shrinkage response to increased pressure potential.

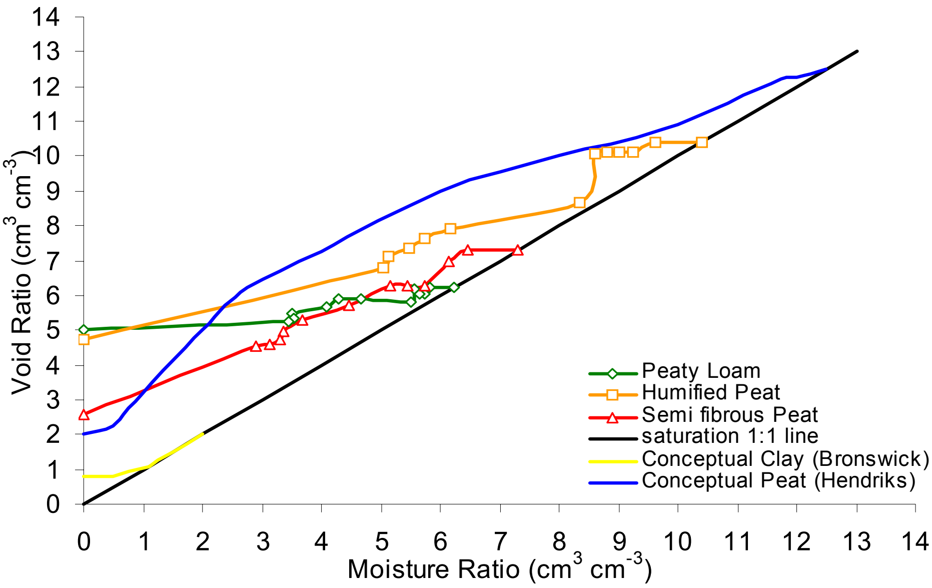


Figure 22: Averaged shrinkage characteristics for West Sedgemoor peats (void ratio is ratio of voids to solids and moisture ratio is ratio of remaining water to solids).

Analysis of variance between the void ratios of the different peats from West Sedgemoor (Table 54, appendix E.9) indicates that the humified peat has considerably greater voids at all pressure potentials than the peaty loam ($p<0.001$). The humified peat does, however, demonstrate unexpectedly greater void ratios at saturation than the semi-fibrous peat, which may result from consolidation similar to that considered for Methwold Fen peat. There are also different rates of decrease in the void ratios of different peat types at each pressure potential ($p = 0.007$). Similarly, the more humified peat demonstrated significantly greater moisture ratios at all tensions than the peaty loam. At different pressure potentials each peat also demonstrates considerably different decreases in the moisture ratio between the different pressure potentials ($p<0.001$). Again, none of the peat soils from West Sedgemoor conform to 'Type I' normal shrinkage (*i.e.* they do not follow the 1:1 saturation line). Also, the initial decrease in the moisture ratio again demonstrates that the air entry point occurs quite rapidly after drainage had commenced. The rapid decrease in the moisture ratio without a simultaneous decrease in void ratio again agrees with the water retention characteristic data for West Sedgemoor peats in section 6.6.3.2; that air entry occurs before -0.2 m pressure potential. However, the humified peat does appear to exhibit the greatest shrinkage potential and it appears to experience a catastrophic loss of voids between -1.0 m and -10 m pressure potential. This collapse of macropores suggests that the soil comes fairly close to its saturated state again. Though the rapid decline in void ratio eventually reduces and the peat again experiences greater moisture loss than loss of voids. The semi-fibrous peat does not exhibit such a radical loss of void spaces though does experience a lesser but earlier decrease in void ratio at about -0.6 m pressure potential. The finding is unusual given that the semi-fibrous peat had exhibited greater total porosity, reduced bulk density, increased hydraulic conductivity and greater water loss under tension, relative to the humified peat. Yet it initially suggests that the semi-fibrous peat is less vulnerable to shrinkage than the more humified peat. Overall, the semi-fibrous peat exhibits a similar degree of change in void ratio to the humified peat. It is therefore surmised that the initial reduction in void ratio is a consequence of the increased over-burden experienced by the semi-fibrous peat in the field due to its deeper position in the soil profile.

Though the void ratios at permanent wilting point (PWP) for West Sedgemoor peats are of similar magnitude to those experienced by West Methwold Fen peats the change in void ratio between saturation and PWP is greater for West Sedgemoor peats. This implies that the less fibrous West Sedgemoor peats are more vulnerable to shrinkage than the Methwold Fen peats. This may be a consequence of the decreased consolidation and lower bulk density of the West Sedgemoor peats.

For the West Sedgemoor peats the change in moisture ratio accounts for 77.7 per cent of the change in void ratio (Table 58, appendix E.9), with a simple linear relationship, such that:

$$\mathrm{VR} = 0.822\mathrm{MR} + 2.29$$

Equation 14: The relationship between void ratio (VR) and moisture ratio (MR) for West Sedgemoor peats

6.6.3.2. Water retention characteristics

Figure 23 depicts the water retention characteristic (WRC) data in Table 60 and Table 63 (appendix E.10). Figure 23 a-c are peats from West Sedgemoor and Figure 23 d-f are peats from Methwold Fen. Dots represent observed soil moisture at each pressure potential and lines represent van Genuchten fitted curves. Dark dots and lines are WRC based on the original volume of peat samples and light dots and lines are WRC based on actual volume. All plots demonstrate that the WRC of all peat types studied in this work exhibit a relatively slow decrease in soil moisture content with increasing pressure potential.

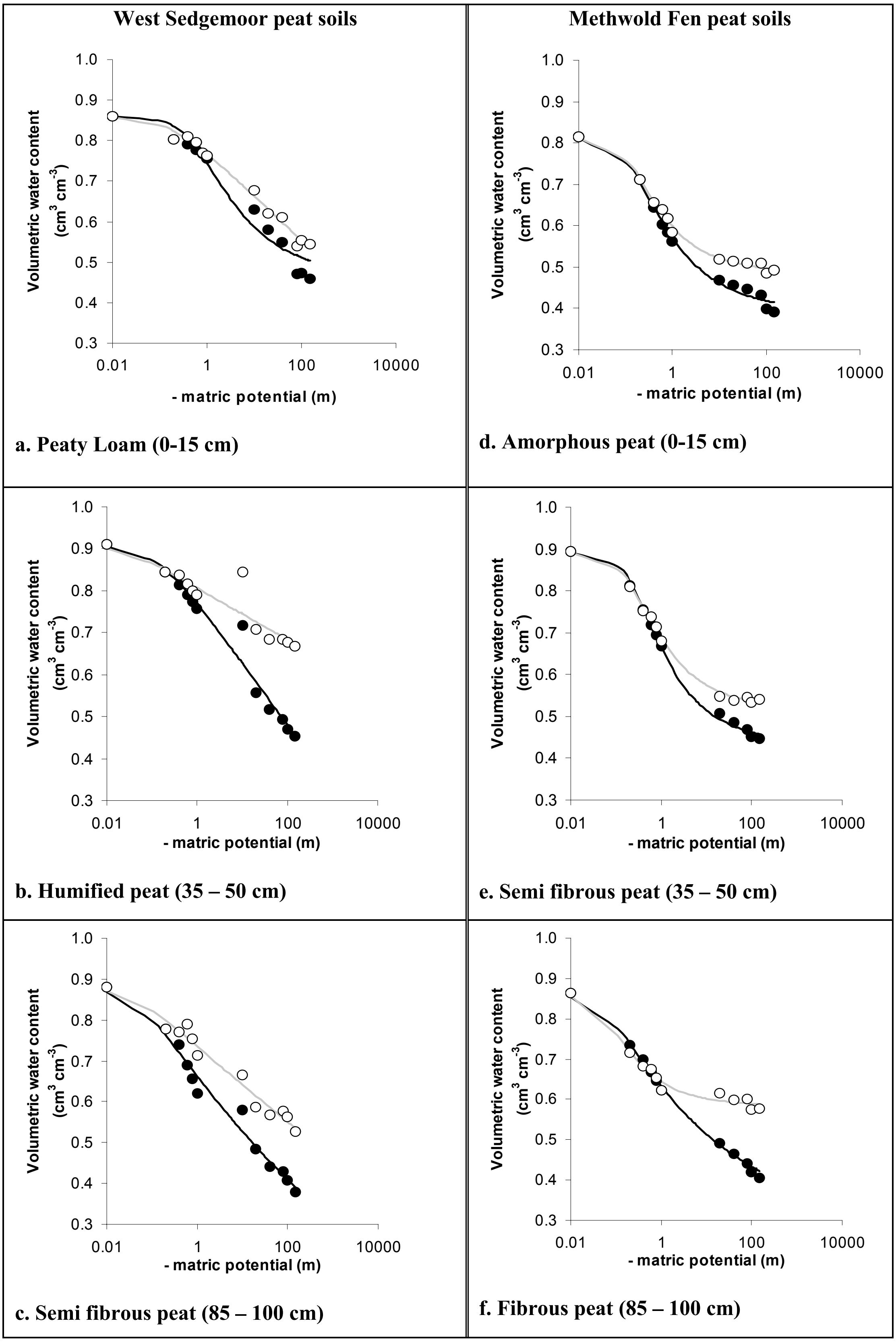


Figure 23: Water retention curves for West Sedgemoor peats a-c and Methwold Fen peats d-f.

There are considerable differences in WRC of each peat when a comparison is made between observed data based on the original and actual volume of sample. This demonstrates the extent to which shrinkage can influence soil moisture content. The divergence in modelled soil moisture content between original and actual soil volume generally occurs between -0.75 and -1.0 m pressure potential for all peats except the semi-fibrous peat from West Sedgemoor. This latter peat divergence occurs at a pressure potential where the peat is close to saturation.

All of the analysed peats maintain residual soil moisture between 0.5–0.7 cm^3 cm^{-3} at PWP (-150 m pressure potential). Generally, however, the more fibrous peats remain relatively wetter than more humified peats at lower pressure potentials but lose relatively more soil water at higher pressure potentials. There are considerable differences in WRC between the different peats, with the Methwold Fen peats exhibiting a more clearly defined logistic curve than the West Sedgemoor peats. Regression analysis (Table 61 and Table 64, appendix E.10) indicates a good correlation between the van Genuchten (1980) fitted model and the observed data for all West Sedgemoor peat types (R^2 = 60.4 %) but this correlation is less evident in Methwold Fen peats (R^2 = 44.5 %).

Analysis of variance of the WRC of West Sedgemoor peats (Table 62, appendix E.10) affirms that the different types of peat exhibit considerable variation in their WRC ($p<0.001$). The peaty loam surface soil displays a marked change in the rate of water loss at about -0.5 m pressure potential whilst the humified and semi-fibrous peats exhibit a continual and steady loss of water at increasing matric potentials. The semi-fibrous peat does, however, lose a greater percentage of soil moisture than either the humified peat or peaty loam; both of which have similar soil water retention at PWP (LSD of 7.8). The smaller pore size of the humified peat and peaty loam in conjunction with the higher ash content of the peaty loam may have increased the degree of adhesion of water to soil particles at pressure potentials approaching PWP.

Analysis of variance of Methwold Fen peats (Table 65, appendix E.10) indicates there are considerable differences in the WRC of these peats ($p<0.001$). All Methwold Fen peats exhibit a more marked logistic curve than West Sedgemoor peats, with the more fibrous peat exhibiting the greatest decrease in moisture of all samples. The fibrous peat also demonstrated the greatest discrepancy between soil moisture based on original volume versus actual volume, affirming that shrinkage has a more marked effect on soil moisture in more fibrous peats.

Table 3 gives the observed soil water content at saturation and the residual moisture content at -150 m pressure potential (PWP) and the modelled parameters determined from van Genuchten's (1980) closed form equation for each peat from West Sedgemoor and Methwold Fen.

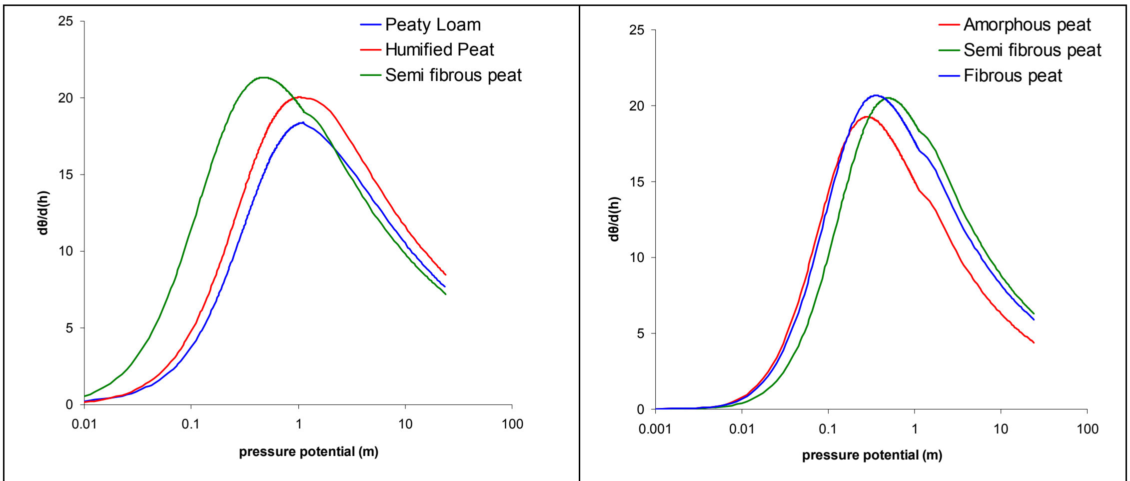
Source	Soil type	α (m^{-1})	Air entry point 1/α (m)	n	m	θsat (%)	θres (%)	Relative % water loss between saturation and PWP	Ksat (m d^{-1})
WSM	peaty loam	2.15	0.47	1.40	0.28	86.05	46.15	46.4	1.51
WSM	humified peat	2.53	0.40	1.37	0.27	90.69	45.32	50.0	1.55
WSM	semi-fibrous peat	5.7	0.18	1.35	0.26	87.88	37.76	57.0	2.3
MF	amorphous	8.64	0.12	1.4	0.29	81.45	40.49	50.3	0.27
MF	Semi fibrous peat	5.07	0.20	1.38	0.28	90.02	44.89	50.1	2.12
MF	Fibrous peat	7.31	0.14	1.37	0.27	88.98	42.17	52.6	2.95

Table 3: Soil moisture content, measured as a percentage, at saturation (θ_{sat}) and at -150 m pressure potential (θ_{res}) and the difference between them; the saturated lateral hydraulic conductivity (m d^{-1}); the van Genuchten parameters ('α', 'm' and 'n') determined by fitting the closed form equation to West Sedgemoor (WSM) and Methwold Fen (MF) observed data (as discussed in section 6.5.3.2) and the calculated air entry point.

Using the alpha value to estimate the air-entry point (1/α) suggests the semi-fibrous peat at West Sedgemoor has a lower air entry than either the peaty loam or the humified peat, at around -0.18 m pressure potential. The more fibrous peats from Methwold Fen have similar calculated air entry points; ranging from -0.14 to -0.2 m pressure potential. However, the surface amorphous peat from Methwold Fen has a peculiarly low calculated air entry point, at -0.12 m pressure potential. After air entry has occurred the semi-fibrous peats generally appear to experience a faster decline in soil moisture content than the more humified peat.

6.6.3.3. Dominant pore size

The dominant pore size was calculated at the point at which δθ/δ(h) is at a maximum. The maximum δθ/δ(h) are plotted in (Figure 24) for peats from both West Sedgemoor (a) and Methwold Fen (b). The maximum rate of change in soil moisture occurs at relatively low pressure potentials. There are small shifts in this maximum δθ/δ(h) for peats from the different research sites and at different stages of degradation. Figure 24 suggests the more fibrous peat from West Sedgemoor has marginally greater maximum δθ/δ(h) and lower pressure potential at which this maximum change in soil moisture occurs. The Methwold Fen peats appear to have generally similar rates of change in soil moisture to one another and similar low pressure potentials at which this maximum rate of loss occurs. However, the amorphous peat does have a lower maximum rate of moisture loss and this occurs at a slightly lower pressure potential.



a. West Sedgemoor

b. Methwold Fen

Figure 24: First order derivation of δθ/δ(h) against pressure potential for West Sedgemoor and Methwold Fen peats.

The pressure head at maximum δθ/δ(h) and calculated dominant pore size for each peat type are given in Table 4.

Source	**Peat type**	**Pressure potential at max δθ/δ(h) in metres**	**Macropore size (µm)**
WSM	Peaty Loam	1.14	26
WSM	Humified peat	1.03	29
WSM	Semi-fibrous peat	0.48	63
MF	Amorphous peat	0.29	105
MF	Semi-fibrous peat	0.50	60
MF	Fibrous peat	0.36	83

Table 4: Air entry point and dominant macropore size for West Sedgemoor (WSM) and Methwold Fen (MF) peats.

The pressure potentials at which maximum drainage occurs suggests the West Sedgemoor peaty loam and humified peats require a relatively higher pressure potential to achieve the maximum rate of drainage, when compared against all other peat samples. The semi-fibrous peat from West Sedgemoor has a greater maximum rate of moisture loss and a lower pressure potential at which this maximum occurs; which is explained by the considerably larger dominant pore size. The West Sedgemoor semi-fibrous peat and the Methwold Fen semi-fibrous and fibrous peats (Figure 24b) are all quite similar in the maximum rate of change and in pore size. The pores are larger in diameter and the pressure potential at which the maxima occur are at equally low pressure potentials. However, the amorphous peat from Methwold Fen is an oddity, with a much lower pressure potential at which maximum moisture loss occurs and a larger dominant pore size to explain it.

6.6.3.4. The relationship between saturated hydraulic conductivity, the maximum change in porosity (dominant pore size) and drainable porosity (specific yield).

The concept of the capillary storage capacity of a soil provides a useful measure of differences between soils' dominant pore sizes. In the peat soils under investigation the capillary storage capacity of all peats, irrespective of maximum δθ/δ(h) or pore size, is very small and the total change in soil moisture content are relatively similar (Table 5 column c).

Source	Soil type	a Maximum Porosity (ϕ) ($cm^3\ cm^{-3}$)	b Soil θ at max δθ/δ(h) ($cm^3\ cm^{-3}$)	c capillary storage (%)
WSM	Peaty Loam	0.86	0.83	3.5
WSM	Humified peat	0.91	0.88	3.3
WSM	Semi-fibrous peat	0.88	0.85	3.4
MF	Amorphous peat	0.81	0.78	3.7
MF	Semi-fibrous peat	0.89	0.86	3.4
MF	Fibrous peat	0.86	0.84	2.3

Table 5: Difference in porosity between saturation and maximum δθ/δ(ψ) *i.e.* capillary storage.

Equally, a regression analysis of the relationship between the dominant pore size calculated from the maximum δθ/δ(h) and the saturated lateral hydraulic conductivity (Figure 25) suggests there is a strong correlation between the two. However, the relationship relies on the removal of the anomalous amorphous peat.

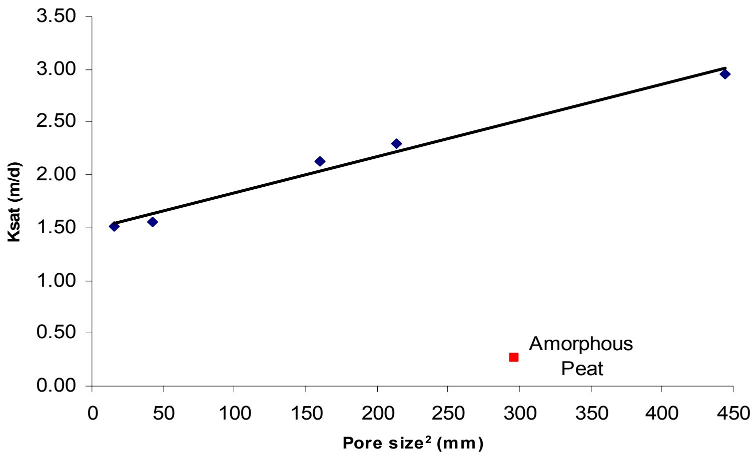


Figure 25: Relationship between the square of the mean pore size and the saturated lateral hydraulic conductivity (Ksat)…after the Hagen- Poiseuille Law.

Given the unstructured and granular nature of the amorphous peat it seemed appropriate to investigate the relationship between dominant pore size and the saturated hydraulic conductivity without the confounding influence of this peat type. In this case the dominant pore size accounts for 96 per cent of the variation in saturated hydraulic conductivity of the different peats (Table 75, appendix E.11) and is explained by the relationship:

$$K_{sat} = [0.0024 PS] + 0.83$$

Equation 15: Saturated hydraulic conductivity as a function of pore size

where saturated hydraulic conductivity (Ksat) is in m d^{-1} and the function of pore size (PS) is in μm.

The strong correlation between the dominant pore size of different peats and their respective saturated hydraulic conductivities is based on the maximum rate of change in moisture content per unit change in pressure head.

An investigation of the relationship between the *effective porosity* (specific yield) of peat and the saturated hydraulic conductivity appears equally valid. Table 6 reports the specific yield of peat based on the Boelter (1968) assertion that the specific yield of peat is best determined at -1.0 m pressure potential. At -1.0 m pressure potential the specific yield of all peats under investigation averages 0.2 cm^3 cm^{-3}; with a mean of 0.18 cm^3 cm^{-3} for West Sedgemoor peats and 0.22 cm^3 cm^{-3} for Methwold Fen peats. These values are comparable with those reported by a number of authors (Boelter 1968, Letts *et al.* 2000, Murtedza *et al.* 2002 and Parkin *et al.* 2004) for the specific yield of a range of peat soils.

Source	**Soil type**	**a** **Maximum Porosity (ϕ) at saturation (cm^3 cm^{-3})**	**b** **moisture content at -1 m pressure potential (cm^3 cm^{-3})**	**c** **Specific Yield (cm^3 cm^{-3})**
WSM	Peaty Loam	0.86	0.73	0.13
WSM	Humified peat	0.91	0.75	0.16
WSM	Semi-fibrous peat	0.88	0.64	0.24
MF	Amorphous peat	0.81	0.57	0.24
MF	Semi-fibrous peat	0.89	0.68	0.21
MF	Fibrous peat	0.86	0.64	0.22

Table 6: Effective porosity (cm^3 cm^{-3}) for West Sedgemoor and Methwold Fen peats

As with the investigation of the relationship between pore size and saturated hydraulic conductivity the confounding effects of amorphous peat meant it was discounted from the analysis. In this case Figure 26 demonstrates the correlation between specific yield and hydraulic conductivity.

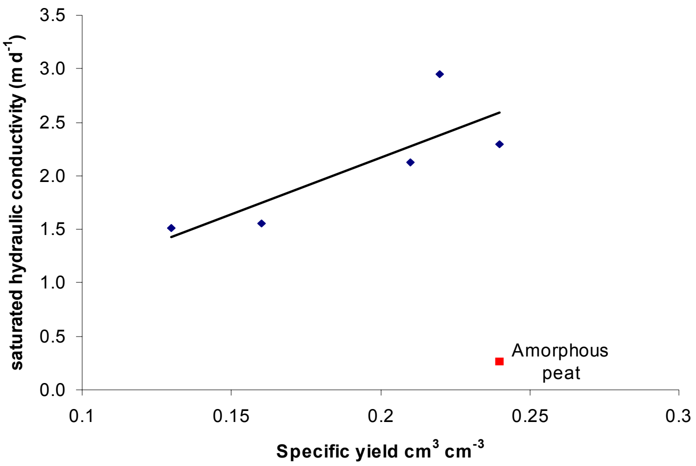


Figure 26: Relationship between specific yield and saturated hydraulic conductivity for peat soils.

The specific yield accounts for 66 per cent of the variation in saturated hydraulic conductivity (Table 76, appendix E.11), with Equation 16 demonstrating the relationship.

$$K_{sat} = 10.62SY + 0.047$$

Equation 16: Saturated hydraulic conductivity as a function of specific yield

where saturated hydraulic conductivity (K_{sat}) is in units of m d^{-1} and specific yield (SY) is in units of cm^3 cm^{-3}.

6.6.3.5. Unsaturated hydraulic conductivity

Figure 27 depicts calculated unsaturated hydraulic conductivity for different peats from (a) West Sedgemoor and (b) Methwold Fen. Under unsaturated conditions the direction of flow is strongly affected by capillary forces and rates of evapo-transpiration and calculated unsaturated hydraulic conductivity is therefore based on vertical saturated hydraulic conductivity; using the van Genuchten (1980) fitting parameter m (Table 77 and Table 78, Appendix E.11). For all peats the calculated unsaturated hydraulic conductivity appears to tend to zero between -0.5 and -1.0 m pressure potentials.

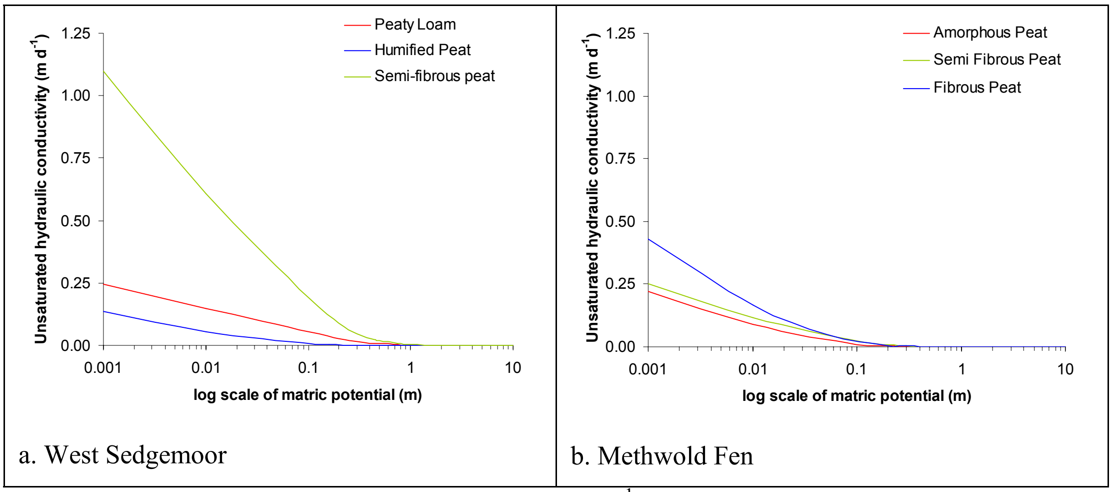


Figure 27: Unsaturated hydraulic conductivity (m d^{-1}) calculated for West Sedgemoor (a) and Methwold Fen (b) according to van Genuchten (1980) parameters.

Only the West Sedgemoor semi-fibrous peat demonstrates a relatively high saturated vertical hydraulic conductivity. The other soils from West Sedgemoor have saturated vertical hydraulic conductivity values below 0.25 m d^{-1}. All peats from Methwold

Fen exhibit saturated vertical hydraulic conductivity lower than 0.5 m d^{-1}, irrespective of their degree of degradation. The West Sedgemoor peats exhibit a much faster decline in saturate hydraulic conductivity but still has a higher pressure potential at which hydraulic conductivity tends to zero (relative to other peats from both research sites). The peaty loam and humified peat from West Sedgemoor experience a relatively similar slow decline in hydraulic conductivity but the higher saturated hydraulic conductivity of the peaty loam means it also tends to zero near a pressure potential of -1.0 m. The Methwold Fen fibrous peat experiences the steepest moisture loss gradient in these samples but all peats tend to zero hydraulic conductivity at lower pressure potentials (-0.2 to -0.5 m) than West Sedgemoor peats.

Using the residual moisture content at -150 m pressure potential as a baseline again suggests that all peats may have a dual porosity system; as a considerable proportion of total porosity does not appear to be involved in flow. The discrepancy between moisture content at which calculated unsaturated hydraulic conductivity tends to zero and the residual moisture content at -150 m pressure potential suggests moisture at higher pressure potentials results from extraction from intra-particulate material rather than inter-particulate material.

6.7. Discussion

As considered by Rowell (1994) for mineral soils, changes in the texture of peat soils were initially assumed to determine the structure of the soil matrix, and hence the capacity for storage and transmission of water. Quantifying the relationship between the SOM and the von Post scale of degradation (von Post, 1924) aimed to identify whether SOM is an important factor governing hydraulic properties in peats and whether there is a link between SOM and the degree of peat degradation.

It is believed that the alluvial peaty loam horizon covering West Sedgemoor occurs because of the management practice of inundating the land with standing water during the winter period. The incorporation of decaying surface vegetation into the settling out mineral material creates an organic soil. A comparison of those soils from West Sedgemoor and Methwold Fen classified as true peats, and accordingly ranked on the von Post scale, indicates they have considerably different SOM content. Though some peats are similarly ranked in terms of degradation it may be that these peats originated from parent material with different quantities of SOM; implying that the botanical composition of a peat soil's parent vegetation, whilst not addressed in this work, should be given greater weight in identifying the textural and possibly hydraulic properties of different peat soils. Given that such similarly ranked peats have significantly different SOM content, the findings indicate that neither the modified or full von Post scale adequately differentiate between peat types on the basis of their SOM content alone. As a descriptor of peat degradation, the modified von Post scale does, however, provide the only current means of differentiating between peat soils at different stages of degradation. The modified von Post scale therefore remains in use in this work for subsequent investigation of storage and flow of water in peat purely to aid differentiation between each soil's properties.

Recent work by Prevost (2004) states that increasing SOM enhances the porosity and structure of mineral soils. The findings of Kay *et al.* (1997) indicate that the dynamic nature or soil pores does, though, cause inconsistent correlations between SOM content and macro-porosity. This thesis shows that in agricultural peat soils the maximum porosity of different peats is highly variable and depends on the degree of shrinkage (under increasing pressure potentials) that different peats experience. Figure 28 demonstrates that under saturated soil moisture conditions the SOM content of the various peats under investigation accounts for 56 per cent of the variation in maximum porosity (Table 44, appendix E.7), as explained by the relationship in Equation 17.

$$\phi = 0.31\text{SOM} + 0.633$$

Equation 17: Relationship between maximum porosity and soil organic matter content.
where total porosity (ϕ) is in units of $cm^3\ cm^{-3}$ and soil organic matter content (SOM) is in units of $g\ g^{-1}$.

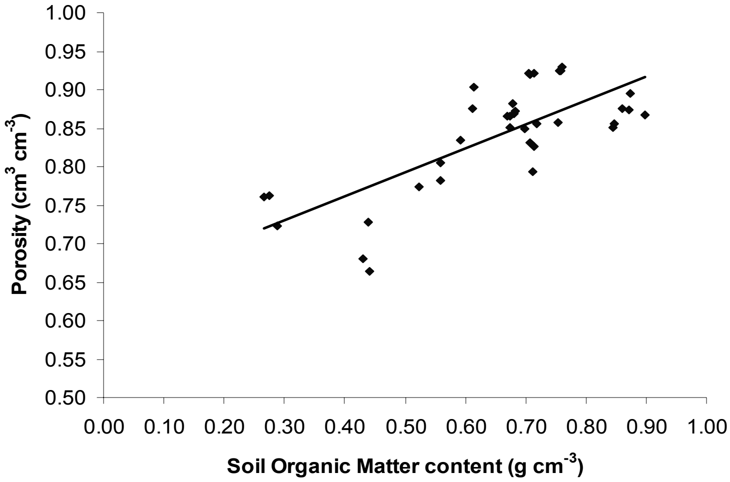
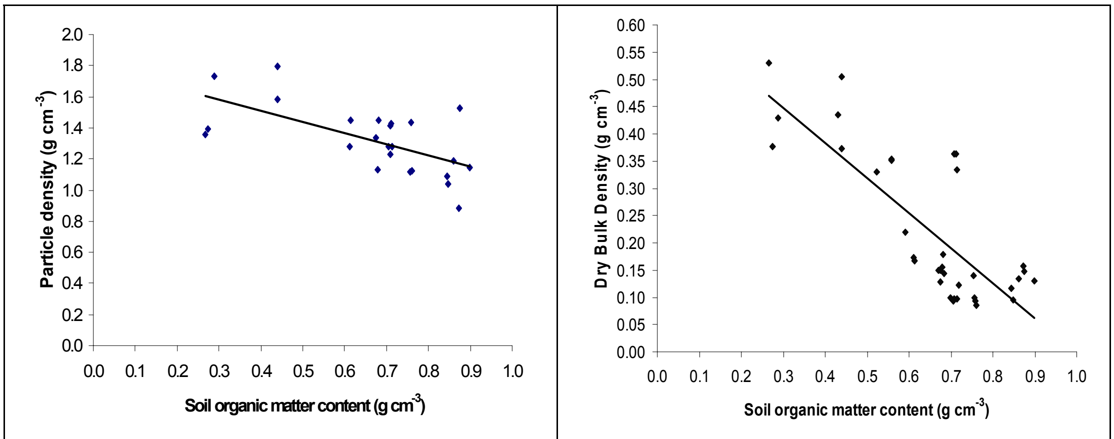


Figure 28: Regression analysis of total porosity against SOM content of all soils from West Sedgemoor and Methwold Fen.

Given the positive correlation between SOM content and maximum porosity a study of the relationship of SOM with dry bulk density and particle density, respectively, was undertaken and is depicted in Figure 29 ‘a’ and ‘b’. A decrease in SOM content correlates with an increase in both particle and dry bulk density. However, the SOM content only accounts for 40 per cent of the variation in particle density but 63 per cent of the variation in dry bulk density (Table 44, appendix E.7). Equation 18 gives the relationship between the latter.

$$\rho_{dbd} = 0.64\text{SOM} + 0.64$$

Equation 18: Relationship between dry bulk density and soil organic matter content.
where dry bulk density (ρ_{dpb}) is in units of g cm^{-3} and SOM is in units of g cm^{-3}.



a. Particle density and SOM.

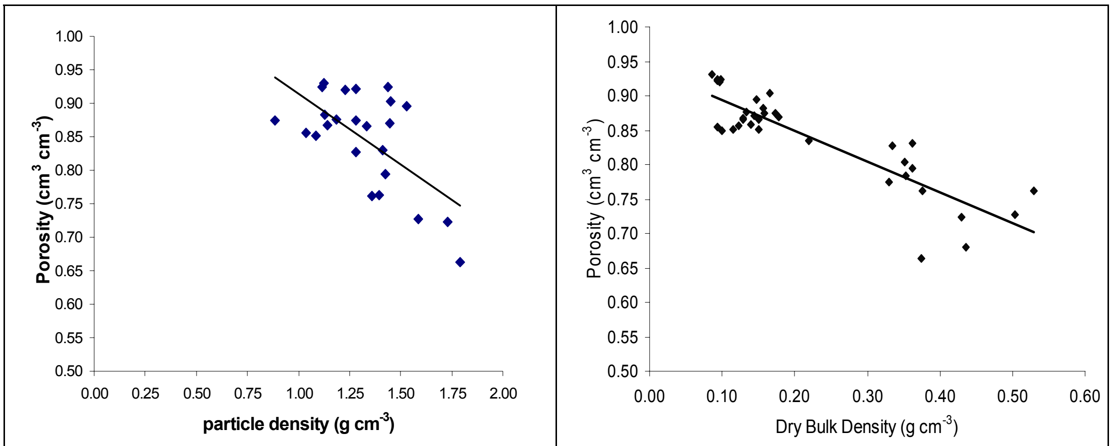
b. Dry bulk density and SOM.

Figure 29: The effect of SOM content on variations in particle and bulk density of all peat soils from West Sedgemoor and Methwold Fen.

Similarly the regression analyses of the relationships of maximum porosity with particle density and dry bulk density, respectively, is depicted in Figure 30 'a' and 'b'. The findings demonstrate that particle density only explains 40 per cent of the decrease in maximum porosity. In contrast, an increase in dry bulk density explains 75.4 per cent of the decrease in maximum porosity (Table 45, appendix E.7). The latter's relationship is given in Equation 19.

$$\phi = -0.45\rho_{dbd} + 0.940$$

Equation 19: Relationship between maximum porosity and dry bulk density.
where total porosity (ϕ) is in units of cm^3 cm^{-3} and dry bulk density (ρ_{dbd}) is in units of g cm^{-3}.



a. Particle density and total porosity. b. Dry bulk density and total porosity.

Figure 30: Correlation between a. particle density (g cm^{-3}) and maximum total porosity (cm^3 cm^{-3}); and b, between dry bulk density (g cm^{-3}) and maximum total porosity (cm^3 cm^{-3}), for all peat soils from West Sedgemoor and Methwold Fen.

A multi-linear regression of the combined contribution of SOM and dry bulk density in determining maximum total porosity (Table 46, appendix E.7) does not account for any more of the variance in maximum porosity (R^2 = 75.4%, $p<0.001$) accounted for by dry bulk density alone, suggesting that SOM and dry bulk density are inextricably linked determinants of maximum porosity at saturation.

The relationship between particle density and porosity are in contrast with Driessen and Rochimah (1976) report that total porosity of peat soils increases marginally with increasing particle density. However, findings on the correlation between bulk density and porosity affirm Driessen and Rochimah's (1976) assertion that the maximum porosity of peat depends primarily on its bulk density. Though the correlation was weak there seems more logic in the findings of this thesis; that a decrease in maximum porosity occurs with increasing particle density. Indeed, in a saturated and unconsolidated state one might expect the constituent fibres of more degraded peats to be more compact (higher particle density) than more fibrous peats and as a result contain less water per unit volume of soil.

The saturated hydraulic conductivity of the peat samples under investigation appears to vary considerably through different planes of sampling; ranging from 0.2-3.2 m d^{-1}. The decrease in saturated hydraulic conductivity between lateral and vertical planes (anisotropy) is especially apparent in more fibrous peats and is believed due to creation of horizontal layering within peat soil horizons when the peat soil's parent plant material originally died back. This is in general agreement with Beckwith *et al.* (2003). Dying back of parent vegetation is likely to have created horizontally layered mats of fibrous material that reduced vertical movement of water whilst enhancing preferential lateral flow paths both between and through plant stem material. Where soil aeration has facilitated degradation of such fibrous layers the difference between lateral and vertical hydraulic conductivity is likely to have reduced considerably, thus explaining why the amorphous peat from Methwold Fen has very similar hydraulic conductivity through both planes. A report by Holden and Burt (2003) also highlights that very high spatial variability in hydraulic conductivity exists in peat soils, possibly due to small-scale variations in long-term soil moisture causing differences in degradation rates of peat. It is believed that the variability in both lateral and vertical hydraulic conductivity of West Sedgemoor semi-fibrous peat is due to such differences and also from variations in the abundance of preferential flow paths between replicate samples. Such variations may also have resulted from spatial variation in shrinkage and swelling rates of the soil matrix.

Overall there is no correlation between maximum porosity and saturated (horizontal) hydraulic conductivity (R^2=0.14). A simple linear regression (Figure 31) does, though, suggest a weak relationship exists between saturated hydraulic conductivity and maximum porosity for Methwold Fen peats (R^2 = 49 %) the lack of correlation is therefore mainly due to the high variability of West Sedgemoor peats.

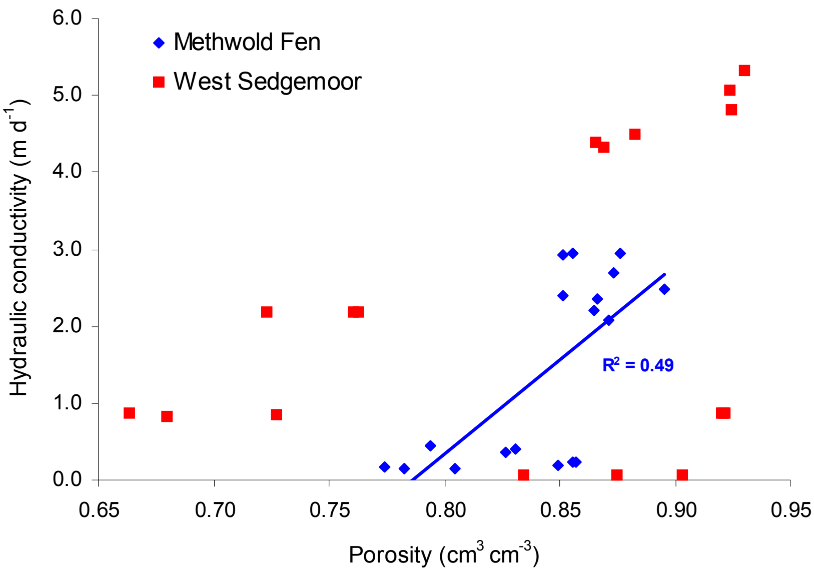


Figure 31: Correlation between hydraulic conductivity and porosity.

The much stronger correlations found between saturated hydraulic conductivity and both the dominant pore size at maximum change in soil moisture (R^2 = 96 %) and with the effective porosity (R^2 = 66 %) appears to affirm the suggestion that a dual porosity system is found all but the unstructured amorphous peat.

Changes in the peats saturated hydraulic conductivity may be reliant on more complex interactions between physical parameters and the maximum porosity, such as the pore size distribution and the inter-connectivity of pores. Indeed, the results indicate that the hydraulic conductivity of the more humified peat from West Sedgemoor is generally greater than the more fibrous peats from Methwold Fen, suggesting that the effective porosity of the peat matrix increases with increasing humification. It seems feasible that the greater structural integrity of fibrous peat soils may lead to greater soil moisture being trapped in the remnant plant cell structures, implying a dual porosity system. One might argue that the dominant pore size and the inter-connectivity of such pores in the semi-fibrous peats at West Sedgemoor is likely to be much greater than those of the more fibrous peats at Methwold Fen which may have collapsed due to greater long-term overburden. The findings are in general agreement with Pearson (1995) who states that both soil water content and saturated hydraulic conductivity are related to the number and continuity of pores in the soil matrix, (particularly the larger macro-pores) but that there remains considerable difficulty in measuring the relationship between these soil attributes.

As the peat soils under investigation are subjected to ever increasing pressure potentials the degree of degradation has a strong effect on the rate of change in maximum porosity (void ratio). This has variable consequences for water flow through the soil matrix. Such change in void ratio does not appear to be directly related to the degree of degradation. Indeed, the change in porosity seems commensurate with the original maximum porosity at saturation (*i.e.* the fibrous peat from Methwold Fen experiences less shrinkage than either the semi-fibrous peat from Methwold Fen or the humified peat from West Sedgemoor). This is believed to result from consolidation experienced by the more fibrous peat in the field because the more fibrous peat comes from a greater depth than the humified peats and suffer greater over-burden pressures.

The study of soil WRC reveals that all peats maintain a relatively high soil water content at -150 m pressure potential (PWP), affirming the supposition of a dual porosity system. The more fibrous peats appear to lose more soil water at low pressure potentials and the more humified peats more soil water at high pressure potentials. The considerable change in void ratio does, however, confound attempts to separate out that proportion of maximum porosity involved in flow of water through the soil matrix (effective porosity). The determination of the maximum rate of change in soil moisture at low pressure potential does suggest the more fibrous peats have generally larger dominant pores (drainable pores) than more humified peats, although the amorphous peat from Methwold Fen is the exception to this rule; with a calculated dominant pores size double that of the fibrous peats. This may be due to the granulated nature of the amorphous peat.

The findings suggest that the size of soil pores of structured peat are strongly correlated to flow of water through the soil matrix under saturated conditions; when no shrinkage (change in porosity) has occurred. Boelter (1968) states that although specific yield is best obtained by measuring the water released over time due to gravitational drainage it is generally measured as the difference in volumetric water content between zero and -1.0 m pressure potential. However, Hillel (1998) states that the classically defined ‘drainable porosity’ (porosity at field capacity using either -1.0 or -3.0 m pressure potential) is a gross approximation of the ‘effective porosity’ of a soil and not a true indicator of that component of a soil’s total porosity involved in flow. Indeed, recent work by Slatyowizc (pers comm.) suggests peat soils may require up to 4 weeks at any given pressure potential for soil moisture to reach equilibrium. The estimates of specific yield at -1.0 m pressure potential in this work are, however, consistent with reports by Armstrong *et al.* (1993) and Armstrong and Rose (1998) that peatlands reclaimed for grazing are liable to have relatively permeable peat at depth. More recently, Parkin *et al*. (2004) also reported similar drainable porosity for West Sedgemoor peats using a modified version of Armstrong *et al.* (1996) ‘DITCH 4’ model.

6.8. Conclusions

The first point to arise from this work is that the von Post scale remains a semi-quantitative tool for practically assessing the relative degree of degradation of similar peats. It should not, therefore, be considered as a suitable means for quantifying the physical and hydraulic attributes of peat soils.

As with mineral soils, increases in peat SOM content do appear to enhance total porosity and the potential for water storage under saturated conditions. However, the degree of consolidation experienced by a peat soil can have an equally strong influence on the total porosity and can result in peats with high SOM having a lower total porosity than peats with less SOM.

Peat soil drainage and rates of rainfall and evapo-transpiration are liable to cause those peat horizons in the vadose zone to experience variable pressure potentials that will lead to short-term shrinkage and swelling.

The study of the different peats WRC provides an indication of the ability of those peats under investigation to retain moisture across a range of pressure potentials and can aid in developing appropriate water-management practices. The water retention and shrinkage characteristic curves of peats in this study suggest that at low pressure potentials the total porosity of all peats remains fairly constant. Indeed, the results concur with the findings of Schothorst (1977), that long-term pressure potential (water table) less than -0.2 m minimises peatland subsidence. However, shrinkage characteristic curves also suggest that at higher pressure potentials humified peats, that have experienced long-term saturation, are equally as likely as fibrous peats, which have experienced long-term consolidation, to suffer collapse at pressure potentials in excess of -1.0 m.

The reasonably slow decline in moisture content for all peats from West Sedgemoor suggests the soil pores are either poorly sorted, the inter-connectivity of macro-pores is reduced, or there is a greater abundance of dead-end pores (*i.e.* more remnant plant tissue with intact cellular structure), all of which are liable to increase the tortuosity of flow through the soil matrix. Conversely, the uniformity of water loss for all Methwold Fen peats suggests that the pores of these peats are more regular and similar in diameter than those from West Sedgemoor. Work by van Genuchten and Wierenga (1976) has shown that knowledge of the maximum porosity of a soil does not adequately consider the abundance of dead end pores or the inter-connectivity of soil pores when quantifying the tortuosity of water flow through the soil matrix.

Though the strong correlation between saturated hydraulic conductivity and the dominant pores at the maximum $\delta\theta/\delta(h)$ suggests the dominant pores of humified peats are equally involved in saturated water flow as the dominant pores in more fibrous peats' the results still allow for the concept of a dual porosity system considered by Genuchten and Wierenga (1976) and Gerke and van Genuchten (1993). Indeed, the rapid tendency of unsaturated hydraulic conductivity at low pressure potentials towards zero and the high residual moisture content at PWP implies no alternative. The concept of a dual porosity system therefore remains highly pertinent, as the more fibrous peat soils are believed to retain a greater percentage of the total soil moisture immobilised in the cellular structure of the soil / plant debris matrix. Equally, though, the reduced size of pores in the humified peats is liable to increase adhesion of soil water to soil particles at higher pressure potentials. The relationship between saturated hydraulic conductivity and total porosity therefore remains complex in peat soils, and drainable porosity at field capacity only provides some indication of the relationship between flow and storage it is confounded by unstructured amorphous peat.

A better indicator of changes in soil water storage is the specific yield of different peats. The specific yields calculated in this work are in general agreement with the findings of other wetland soil studies (Parkin *et al.* 2004, Armstrong *et al.* 1993, Armstrong and Rose 1998). There is a strong correlation between specific yield and saturated hydraulic conductivity in this work, though the relationship is weaker than the one between dominant pore size and saturated hydraulic conductivity. As specific yield is a good indicator of storage and movement of water in peat soils it is considered further during larger-scale investigation of soil water management and the potential of sub-irrigation to enhance water-table levels (chapter 8).

Generally, the study of physical and hydraulic attributes of peats at different stages of degradation suggests that the ability of water-management intervention to improve storage and flow of water under saturated soil moisture conditions is as equally influenced by the degree of consolidation (change in bulk density) as it is by the degree of organic matter degradation. This demonstrates the importance of land-use intensity in pre-determining the effectiveness of water-management intervention. Drainage practices and increased over-burden pressures from intensive agricultural activity can cause greater consolidation and macropore collapse and lead to increased dry bulk density of more fibrous peats.

When all points of this study are considered together they suggest that a change in land-use practice would be required to re-establish the water storage capacity and flow of water in the more fibrous, though highly consolidated, peats. It could be argued, however, that over the short-term the water storage potential of the more fibrous peats is not the important issue for sustaining peat soils; as the deeper and more fibrous Methwold Fen peats, although having a lower porosity, have not degraded to the same extent as the deeper peats at West Sedgemoor.

7. The mineralisation of peat with changing soil moisture, temperature and nutrient amendment.

7.1. Introduction

Discerning changes in microbial respiration across a range of soil moisture, temperature and nutrient amendments elucidates optimal conditions for respiratory activity and informs which conditions should be avoided if the water-management strategy is to minimise organic carbon mineralisation as CO_2-C [12]. Controlled microcosm experiments investigate the importance of soil moisture, temperature and nutrient amendment on the mineralisation of the organic carbon in peats at different stages of degradation.

Early work by Srivastava and Singh (1991) found the functional capacity of a soil resource is strongly linked to the soil's microbial biodiversity. According to the FAO (Bunning, S. and A. Montañez, 2002), over recent years sustainable agricultural management has moved away from the conventional focus aimed at overcoming soil chemical and physical constraints (such as nutrient deficiencies and compaction) to:

"….a focus on soil health that is centred on soil biological management and interactions among components of the soil system and human management practices" (Bunning, S. and A. Montañez, 2002).

Although the microbial status of a soil is often used as an indicator of soil health in peat soils such microbial respiratory activity is also a primary indicator of a peatlands propensity to degrade, and therefore the basic expression of unsustainable peatland management for agriculture. Schothorst (1977) for example, determined that such biochemical oxidation of SOM accounted for 52 per cent of the total subsidence found in Dutch peatlands, with the remainder being ascribed to irreversible shrinkage and consolidation.

[12] CO_2-C is that proportion of organic carbon attributed to mineralisation of organic carbon as CO_2. It is a widely used concept for considering the loss of organic matter from soil systems due to aerobic microbial mineralisation of organic matter.

Zak *et al.* (1999) suggest that soil respiration is optimal at moistures equating to field capacity, whilst research on decomposition of organic matter indicates aerobic microbes generally function best at 60 per cent saturation of soil pore spaces (Fogarty and Tuovinen 1991, Golueke 1972, Poincelot 1972). If such soil moisture conditions provide an optimal environment for microbial respiration across a range of degraded peat soils then such knowledge may facilitate the creation of generic water-management strategies to minimise the degradation rates of all peat types. The importance of water content in peat soil respiration has previously been demonstrated in laboratory microcosm experiments (Aerts and Ludwig 1997, Blodau and Moore 2003), the effect of temperature in laboratory incubation experiments (Chapman and Thurlow, 1998) and changes in soil nutrients by Heathwaite (1990). A comprehensive study on the effect of soil water content, temperature, nutrient additions and depth of soil horizon on CO_2 emission from mineral soils has also been carried out by several authors (Fierer *et al.* 2003a-b, Fierer and Schimel 2002). Despite the combined importance of these factors in controlling CO_2-C emission from peat soils, and their management in a way that could potentially reduce atmospheric warming, there are few controlled studies (Moore and Dalva 1997, Chow *et al.* 2006) of the combined effect that soil water content, temperature and nutrient availability have on CO_2-C efflux from such peat soils.

The effect of soil water-management practices on soil and water biochemistry (temperature, pH, nutrient dynamics) are generally accepted to influence the soil microbial community's size, type and propensity to mineralise organic matter (Bridgham and Richardson 1992, Brake *et al.* 1999, Haragushi *et al.* 2002, Fisk *et al.* 2003). A greater understanding of how these factors influence peat soil degradation could enhance future land and water-management practices, taking into account regional and seasonal variations in climate and land-use type and intensity.

7.2. Aim

To examine the influence of soil water content, temperature and nutrient amendment on microbial mineralisation of SOM in peat microcosms from two peatlands of contrasting land-use: One an intensively farmed agricultural enterprise in the Norfolk

Fens; the other a wildlife conservation site in the Somerset Moors under a prescribed water-management regime and subject to low intensity summer grazing.

7.3. Objectives

- To investigate the effects of peat soil moisture and atmospheric temperature on basal soil respiration rates and microbial biomass.
- To study the importance of soil carbon content and availability, and amendment of the carbon to nitrogen ratio, on soil respiration.

7.4. Outline Methods

The study of soil health considers three aspects of soil microbiology:

1. The rate of microbial respiration.
2. The abundance of microbes in the soil.
3. The type of microbial community

All three of these microbial community facets are affected by niche conditions; which include soil moisture, temperature, nutrient availability (competition for resources) and soil pH. The water-management regime underpins all of these environmental conditions. Microbial respiration rates of different peat soils (also used as a proxy for microbial abundance) were therefore investigated under controlled soil moisture, temperature and nutrient amendments in the laboratory. The third aspect of soil health (*i.e* microbial community structure) is considered in detail in Chapter 9.5.3, as soil sample analyses were undertaken during field scale investigations in order to reduce perturbation of the microbial community.

7.4.1. Basal respiration

Laboratory analysis of organic carbon mineralisation involved monitoring soil respiration from very small samples. In this way the soil water content, atmospheric temperature and nutrient status can be readily controlled.

- 10 g (dry weight) sub-samples of peat at differing stages of degradation were sampled from bulk soil samples collected from West Sedgemoor and Methwold Fen research sites.
- The moisture content of each sample was controlled by saturating each sample for 48 hours and then applying one of four pressure potentials (-0.1, -0.5, -1.0 and -10 m) to the soil sample for a period of two weeks. The soil water content for each peat type at each pressure potential was calculated from knowledge of individual soils WRC (Chapter 6.6.3.2). .
- The samples were covered with plastic sheeting to prevent evaporation and placed in a temperature controlled environment of 10, 20 or 30 ºC for a period of 12 hours to facilitate microbial acclimation to that temperature. This time period was longer than the 6 hour acclimation period employed by Fierer *et al*. (2003) but aimed to maximise microbial acclimation whilst minimising changes in the soil water content of the sample by evaporation.
- Each sample was placed in gas tight 530 ml Mason jar and returned to its previous incubation environment.
- Air samples were extracted from the closed chamber head-space by inserting a needle through a rubber septum and drawing off 5 ml of air at 3, 6 and 12 hours points.
- Air samples were analysed for CO_2 concentration within 24 hours of collection using a CE Instruments 8000 series gas chromatograph and hot wire detector attached to an HLPC Technology Prime chromatography data station.
- The average hourly CO_2 efflux rate was determined by averaging samples collected at 3, 6 and 12 hour intervals.

7.4.2. Substrate induced respiration, microbial biomass and microbial respiration efficiency.

A number of methods exist to determine soil microbial biomass, which is usually expressed as Biomass-C. The substrate induced respiration method (Anderson and Domsch, 1978) relies on soil microbes' preferential uptake of an easily degradable carbon substrate (glucose) to give an increase in respiration. Though most micro-organisms in the soil are dormant (Jenkinson and Ladd, 1981) and their rate of respiration is low, the increase in respiration before cellular growth is related to the substrate-responsive biomass in the soil (Anderson and Domsch, 1978). Anderson and Domsch (1978) determined that glucose was the most readily available form of energy and carbon that soil microbes could use for metabolic processes. Glucose amendment was therefore used to determine microbial biomass in this work.

- To determine the microbial biomass under different soil moisture conditions 5 replicate samples were initially saturated for a period of 48 hours then subjected to one of 4 pressure potentials (-0.1, -0.5, -1.0 and -10 m) for a period of 2 weeks.
- At the end of the two week period samples were rapidly sieved (2 mm sieve), covered with plastic sheeting (to minimise evaporation) and placed in a temperature controlled environment (22 ºC) for a period of 12 hours to acclimate the microbial community to that temperature (Fierer *et al.*, 2003) whilst minimising changes in the soil water content of the sample by evaporation.
- After the 12 hour period the desired wet weight of peat sample (based on 1 g dry weight) was amended with glucose in powder form (75 mg glucose-C g soil^{-1}) and the amended soil placed into 120 ml gas tight Mason jars.
- Samples were returned to the temperature controlled environment for a period of 4 hours (Degens and Harris, 1997) to maximise respiration whilst avoiding the microbial population growth phase.
- After 4 hours 1 ml air samples were extracted from the Mason jars by inserting a needle through a rubber septum in the top of the jar and extracting the sample into a syringe.
- Samples were analysed immediately for CO_2 concentration using a CE Instruments 8000 series gas chromatograph and hot wire detector attached to an HLPC Technology Prime chromatography data station gas chromatography.
- Microbial Biomass-C was determined using the equation proposed by Anderson and Domsch (1978)[13]:

[13] A fuller description of the standard substrate induced respiration method is given in British Standards (1997).

$$X = 40.4Y + 0.37$$

Equation 20: Anderson and Domsch (1978) equation for determining microbial Biomass-C from respiration.

where X is the microbial Biomass-C (µg biomass-C g dry soil^{-1}) and Y is the microbial respiration rate (ml CO_2 g dry soil^{-1} hr^{-1}).

The above procedure was also used to investigate the effect on respiration of additional substrate at 10 to 30 ºC. However, Anderson and Domsch (1978) equation for calculating microbial biomass from substrate induced respiration was specifically developed where air temperature is maintained at 22 ºC. The additional findings could only therefore be used to investigate the effects temperature on different peats respiration rate when a readily available substrate was present. This was useful to investigate whether changes in temperature alter the preferential uptake of root exudates over soil organic matter (i.e. are there differences in mineralisation rates between peat types due to the type of carbon pool and predominant microbial community).

7.4.3. Soil organic carbon (SOC) content and C-mineralisation with amended C:N ratio

The soil C:N ratio is described by Bengtsson *et al.* (2003) as an indicator of a soil's potential for organic matter decomposition. Other workers (Blagodatsky and Richter, 1998) state that 'available organic carbon' (labile carbon) is a better indicator of soil potential for respiratory activity.

This work aimed to investigate the importance of SOC content and the C:N ratio on the mineralisation of organic matter. By analysing the SOC and C:N ratio of peat samples at different stages of degradation and then monitoring the basal rate of microbial respiration of these samples would allow the importance of organic carbon availability and of C:N ratio to be assessed. Subsequent amendment of these peat samples with Nitrogen (in the form of Ammonium Nitrate) and analysis of the rate of microbial respiration under changed C:N ratios made it possible to investigate the importance of SOC and C:N ratio on the rate of SOM mineralisation.

- The un-amended carbon and nitrogen content of triplicate peat samples (at different stages of degradation) was analysed by thermal conductivity using a Vario EL CNS analyser.
- The moisture content of triplicate samples of each peat type was altered by saturating samples for a period of 48 hrs and then applying one of a range of pressure potentials for a period of two weeks (-0.1, -0.5, -1.0 and -10.0 m) using either sand-table or pressure membrane apparatus.
- Samples were then sieved through a 2 mm sieve and rapidly covered with plastic sheeting to minimise evaporation.
- Samples were incubated at 10, 20 or 30 ºC for 12 hours to acclimate soil microbes to the new temperature regime.
- The equivalent of 1 g (dry weight) of peat was placed in a 120 ml gas tight Mason jar and amended with Ammonium Nitrate Solution (NH_4NO_3)[14] to adjust the C:N ratio to one of three ratios (10:1, 5:1 2.5:1).
- Samples were incubated for a further period of 4 hrs (Degens and Harris, 1997) at the prescribed temperature of 10 ºC.
- After 4 hrs 1 a ml air sample was extracted through a rubber septum from each sealed Mason jar using a needle and syringe.
- Samples were analysed immediately for CO_2 concentration using a CE Instruments 8000 series gas chromatograph and hot wire detector attached to an HLPC Technology Prime chromatography data station gas chromatography.

7.5. Results

Analysis of long-term peat soil temperature profiles from a peatland close to the Methwold Fen research area (Figure 32) indicates that over the period 1995 to 2002 peat soil temperatures ranged from +4 to +19 ºC through the upper metre of peat, with an average long-term soil temperature of 10 ºC. Air temperatures at the same location and over the same period ranged from -10 to 31 ºC.

Observation of water-table conditions encountered during field investigations (Chapter 8) suggests peats experience moisture conditions corresponding to pressure

[14] NH_4NO_3 was prepared at a concentration of 50 g N l^{-1}.

potentials between -0.1 and -10.0 m. Accordingly, microbial respiratory activity of different peat soils was analysed at pressure potentials of -0.1, -0.5, -1.0 and -10.0 m and temperatures of 10, 20 and 30 ºC; simulating those conditions experienced in the field, but with particular emphasis on respiratory activity at the long-term average soil temperature of 10 ºC.

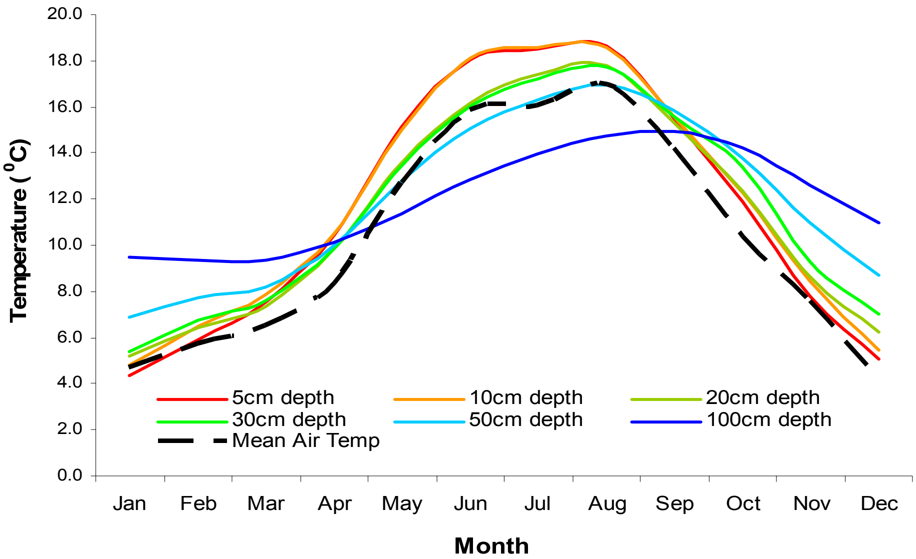


Figure 32: Average 8 year soil temperature profile from 1995 to 2002 (provided by ADAS, Arthur Rickwood experimental husbandry farm, Cambridgeshire). These soil temperatures relate to atmospheric temperatures ranging from -10 to 31 ºC, with a long-term mean atmospheric temperature of 9.8 ºC.

7.5.1. Basal respiration

Figure 33 (a-c) shows the plots of basal respiration of peat soils against moisture content and temperature for various peat horizons from the extensively grazed conservation peatland at West Sedgemoor, Somerset. Figure 33 (d-f) shows plots of basal respiration of peat soils against moisture content and temperature from different peat horizons from the intensively farmed peatland at Methwold Fen, Norfolk.

The basal respiration rates, reported as CO_2-C, obtained for the 3 depths at West Sedgemoor have an average of 4.90 µg CO_2-C g dry soil^{-1} hr^{-1} (ranging from 0.45 to 17.87 µg CO_2-C g dry soil^{-1} hr^{-1} (200, 0.24) across the moisture and temperature range. The basal respiration rates, obtained for the 3 depths of peat at Methwold Fen and over the 4 pressure potentials have an average of 4.96 µg CO_2-C g dry soil^{-1} hr^{-1} (ranging from 0.12 to 19.99 µg CO_2-C g dry soil^{-1} hr^{-1} (201, 0.20).

The findings for basal respiration at incubation temperatures from 10 – 30 ºC are similar to the long-term rates reported by Chow *et al.* (2006), which ranged from 1 – 20 µg CO_2-C g dry soil^{-1} hr^{-1}. Findings are also similar to Fierer *et al.*'s (2003b) results under different pressure potentials (2 – 30 µg CO_2-C g dry soil^{-1} hr^{-1}) but lower than the total range reported by Fierer *et al.* (2003b); which ranged from 10 – 210 µg CO_2-C g dry soil^{-1} hr^{-1}.

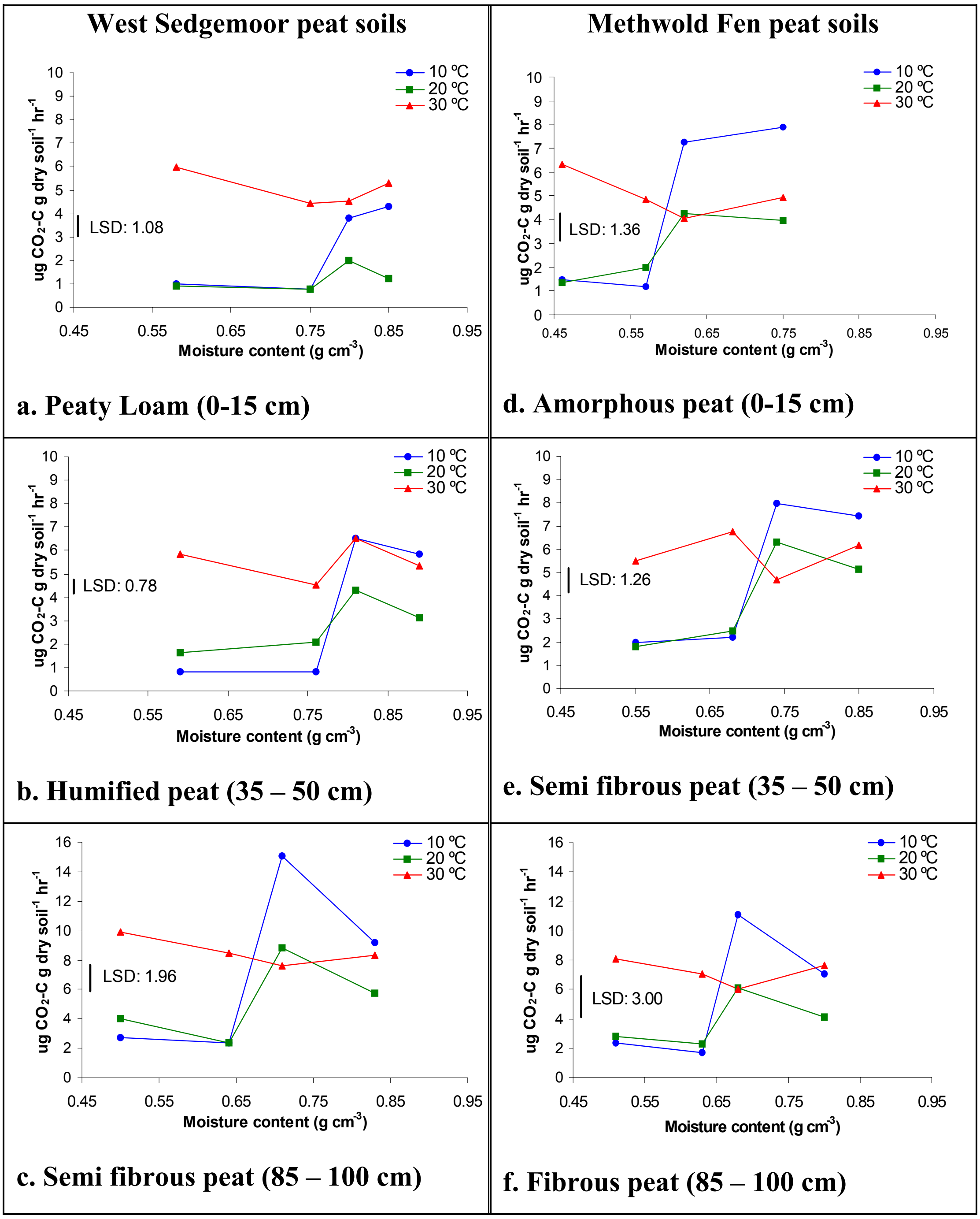


Figure 33: Soil respiration rates from West Sedgemoor and Methwold Fen at 3 depths: a/d: 0 - 15 cm b/e: 35 - 50 cm and c/f: 85 - 100cm.

Overall, there are no significant differences in soil respiration rates between peats from either West Sedgemoor or Methwold Fen ($p=0.17$). However, there are significant variations in the respiration rate between different peat horizons ($p<0.001$), soil moistures ($p<0.001$) and temperatures ($p<0.001$).

7.5.1.1. Effect of soil water content

The plots in Figure 33 indicate that for low soil water contents (corresponding to between -1 and -10 m pressure potential) there is little difference in the rate of respiration between any peats at 10 and 20 ºC but considerably greater respiration rates in all peats at 30 ºC. At higher soil water contents (corresponding to -0.5 to -0.1 m pressure potential) all peats show a sharp increase in respiration rate at 10 and 20 °C but not at 30 ºC. For sub-surface peats there is a highly visible peak in respiration rate at -0.5 m pressure potential at both 10 and 20 °C. This peak also occurs in surface soils from both research sites but to a lesser extent (Figure 33).

7.5.1.2. Effect of depth / peat type:

At West Sedgemoor, there generally appears to be an increase in the rate of respiration with depth / peat type. The respiration rate in the bottom layer is considerably greater than in the middle and top layers. (LSD: 1.72, $p<0.001$). However, the difference between the respiration rate in the bottom layer and the other layers is much greater at higher soil water contents, particularly around -0.5 m pressure potential. This difference in respiration rate between the various peat horizons also decreases at greater temperatures; being maximal at the lowest temperature of 10 °C (Figure 33 b/c and e/f). Conversely, there is no marked effect of depth / peat type across all temperatures or soil water potentials in Methwold Fen peats (Figure 33 d-f).

7.5.1.3. Effect of temperature:

The data in Figure 33 is portrayed in a slightly different manner in Figure 34, in order to aid interpretation of the effects of temperature. Each individual plot shows the effect of one temperature condition on all the peat soils from one location. Plots 'a'-'c' are for West Sedgemoor peats and plots 'd'-'f' are for Methwold Fen peats. Temperature increases in 10 ºC steps from 'a'-'c' and from 'd'-'f'.

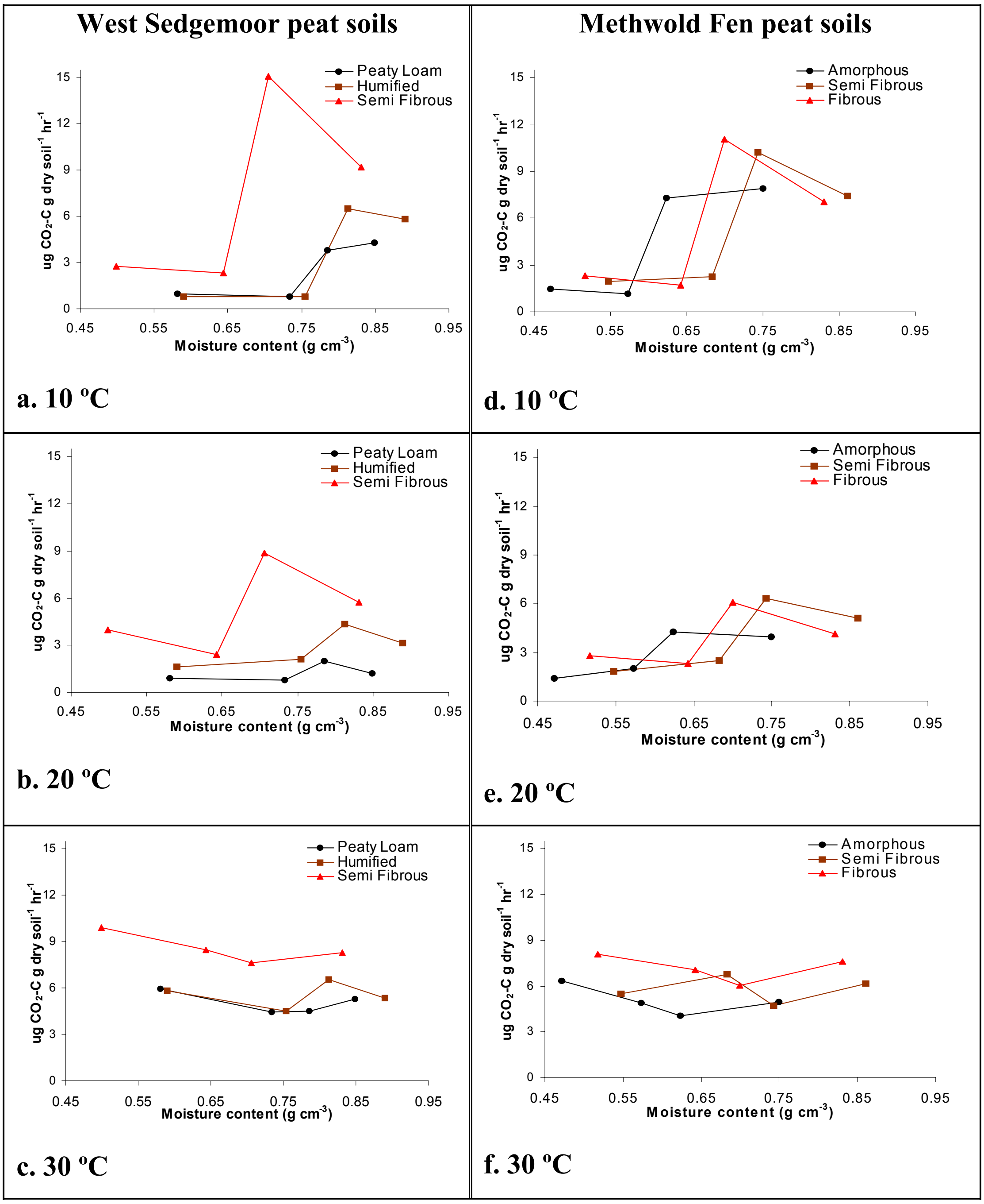


Figure 34: Soil respiration rates from West Sedgemoor and Methwold Fen peats at 3 different temperatures: a/d: 10 ºC b/e: 20 ºC m and c/f: 30 ºC

In West Sedgemoor peats there is considerable increase in soil respiration of the surface peaty loam when temperature decreases from 20 to 10 °C. The same is true in the humified and semi-fibrous peat but not to the same degree (plots 'a' and 'b').

However, the effect only becomes apparent at soil moistures corresponding to pressure potentials less than -0.5 m. Generally, there also appears to be an increase in respiration rate when air temperature rises from 20 to 30 °C for all peats but, contrary to change in respiration corresponding to the decrease in temperature from 20 to 10 ºC, this increase is less marked. The averaged effect of a change in temperature from 20 ºC to either 10 or 30 ºC is generally an increase in soil respiration.

The amorphous and semi-fibrous Methwold Fen peats (Figure 34 d and e) both show a marked increase in respiratory activity when temperature decreases from 20 ºC to 10 ºC with increasing soil moisture (corresponding to -0.1 to -1.0 m pressure potential). When the temperature is increased from 20 to 30 ºC respiratory activity appears to show a greater increase when the peats have lower soil moisture content (corresponding to -1.0 to -10 m pressure potential).

When comparing the change in respiration rate of all peats from 20 °C to either 10 or 30 °C the soil moisture conditions closer to saturation (corresponding to -0.1 m pressure potential) causes Q_{10} [15] to reduce considerably. At moisture contents corresponding to -0.5 m pressure potential, however, the rates of respiration for 4 out of 6 peats increases dramatically (excepting the peaty loam and humified peat from West Sedgemoor (Figure 33 ‘a’ and ‘b’). Generally, when soil moisture content is low respiration rates are significantly greater at 30 °C than at 10 °C (LSD: 1.72, $p<0.001$) but the same is not true when soil moisture is higher.

Table 7 depicts the Q_{10} values for each peat type and source across two temperature ranges; 20 to 10 ºC and 20 to 30 ºC (all samples were pre-conditioned at 20 ºC).

[15] Q_{10} is the change in rate of a chemical reaction with a 10 ºC change in temperature, based on the activation energy of a catalyzed reaction according to the Arrhenius relation.

Location*	Peat type	Temperature (°C)	Mean Q_{10}**
WSM	Peaty loam	20 – 10	1.9
WSM	Peaty loam	20 – 30	4.7
WSM	Humified	20 – 10	1.5
WSM	Humified	20 – 30	2.2
WSM	Semi fibrous	20 – 10	1.2
WSM	Semi fibrous	20 – 30	2.1
MF	Amorphous	20 – 10	1.3
MF	Amorphous	20 – 30	2.3
MF	Semi fibrous	20 – 10	1.3
MF	Semi fibrous	20 – 30	1.9
MF	Fibrous	20 – 10	1.3
MF	Fibrous	20 – 30	2.2

Table 7: Q_{10} values for different peat types. (* WSM is West Sedgemoor and MF is Methwold Fen. **underlined values indicate negative trend in Q_{10}).

The West Sedgemoor peaty loam surface soil has a mean Q_{10} value between 20 and 30 °C much higher than all other peat types (Table 7). All other peats display lower mean Q_{10} values across this temperature band; ranging from 1.9 to 2.3. The mean Q_{10} values between 20 and 30 °C at low water content (corresponding to 1 and 10m tension) have a greater range of mean Q_{10} values; from 2.2 to 6.5 whereas at high water content (corresponding to 0.1 and 0.5m tension) the range is smaller; from 0.7 to 4.4.

Generally, the increase in temperature from 20 to 30 °C results in a considerable increase in respiration for all 6 peats at lower moisture contents. However, at higher water content the semi fibrous peat from Methwold Fen does not appear to differ greatly in respiration rate (LSD: 1.72, $p<0.001$).

The decrease in temperature from 20 to 10 °C indicates there is an increase in respiration, as mean Q_{10} values are greater than 1. Contrary to the Q_{10} values across the higher temperature range the Q_{10} values across the lower temperature band are greater at the wetter end; ranging from 1.5 to 3.5. Respiration is considerably higher in this cooler, wetter environment (LSD: 1.72, $p<0.001$). At lower water contents, in this cooler environment, there is, however, a more conventional decrease in respiration rates, with the mean Q_{10} values ranging from 0.4 to 1.1.

7.5.2. Microbial biomass and respiration efficiency

Substrate induced respiration during the first 4 hours of incubation at 22 ºC ranged from 5.8 to 27.4 µg CO_2-C g soil^{-1} h^{-1} across the 4 soil moisture conditions (Table 8). These values are slightly higher than the findings of Fisk *et al*. (2003) who reported substrate induced respiration at 22 ºC ranging from 1.2 to 11.1 µg CO_2-C g soil^{-1} h^{-1}. Biomass-C findings (Table 8) do compare with Brake *et al*. (1999) who reported values (by SIR) ranging from 0.27 to 4.6 mg g dry soil^{-1}. Brake *et al*. (1999) also discuss the importance of the respiratory efficiency per unit microbial biomass (qCO_2[16]), suggesting that in aerated surface horizons the more efficient use of readily available substrate leads to greater efficiency in microbial activity and a decrease in qCO_2 (*i.e.* less CO_2 is evolved per unit biomass). The qCO_2 findings in this work are higher at all depths than those reported by Brake *et al. (*1999) but agree with Brake *et al. (*1999) trend; that more CO_2-C is evolved per unit biomass in deeper peats than surface horizons at both research sites.

Source*	Soil type	Mean SIR (µg CO_2-C g^{-1} h^{-1})	Microbial Biomass (mg g soil^{-1})	Mean qCO_2-C** (µg CO_2-C mg Biomass-C^{-1} h^{-1})
WSM	Peaty loam	15.8 (20, 0.6)	1.52 (20, 0.05)	7.4
WSM	Humified	11.0 (20, 0.6)	1.20 (20, 0.04)	7.7
WSM	Semi fibrous	10.4 (20, 0.8)	1.09 (20, 0.07	11.5
MF	Amorphous	17.2 (20, 1.6)	1.59 (20, 0.13)	5.1
MF	Semi fibrous	13.1 (20. 0.5)	1.30 (20 0.06)	8.0
MF	Fibrous	11.2 (20, 0.4)	1.23 (20, 0.08)	9.6

Table 8: Substrate Induced respiration at 22 ºC, microbial biomass and basal respiration efficiency per unit biomass. (*WSM is West Sedgemoor and MF is Methwold Fen. ** Calculated mean across all moisture contents).

Analysis of variance of Biomass-C in West Sedgemoor peats (Table 102, appendix F.3) indicates there is significantly more Biomass-C in the surface horizons than in the sub-surface horizons ($p<0.001$). There is also significantly less Biomass-C at higher pressure potentials ($p<0.001$). Similarly, at Methwold Fen analysis of variance (Table 103 appendix F.3) indicates there is significantly more Biomass-C in surface horizons than at depth ($p<0.001$) and at at lower pressure potentials ($p<0.001$).

[16] qCO_2 is the respiratory efficiency per unit microbial biomass. The lower the qCO_2 the greater the efficiency ber unit biomass.

However, qCO_2 values are greater in deeper horizons than in surface horizons (Table 8), suggesting microbial respiration efficiency decreases at depth. qCO_2 is also greater in all peat horizons at West Sedgemoor than in corresponding horizons at Methwold Fen. However, the change in qCO_2 from surface to sub-surface peats also appears more marked between the Methwold Fen agricultural peats than between those of West Sedgemoor. This suggests that though there is greater organic carbon (Table 9, section 7.5.4) in the lower (more fibrous) horizons, the organic carbon pool is more recalcitrant and microbes have to work harder to metabolise it.

7.5.3. Substrate induced respiration at different temperatures

It is believed that below ground respiration on peat soils from West Sedgemoor is mainly due to microbial metabolisation of root exudates and not of the organic matter in the peat. Billings *et al.* (1977) estimated that root participation in soil respiration accounts for between 30–70 per cent of total respiration, depending on habitat. Though monitoring of below ground respiration followed the standard practice of clipping surface vegetation prior to monitoring, the root system was not disturbed. It seems logical that a relationship exists between the rate of below ground respiration and the amount of surface biomass.

Changes in soil microbial respiration after addition of an easily metabolised sugar (glucose) are given in Figure 35. Each plot shows the effects of substrate induced respiration across a range of temperatures for a specific peat type. All plots also depict the effects of pressure potential on soil respiration. Plots a-c depict the peats from West Sedgemoor and plots d-f depict the peats from Methwold Fen. As with C:N amended soils (section 7.5.4) the results of glucose amendment were preconditioned by sieving. Hence the results are reported against pressure potential rather than soil moisture. The sample size and standard error of the mean are given in parentheses.

Substrate induced respiration at 10 ºC averaged 14.69 μg CO_2-C g^{-1} hr^{-1} (57, 0.88) on West Sedgemoor peats and 15.61 μg CO_2-C g^{-1} hr^{-1} (58, 1.22) on Methwold Fen peat. At 20 ºC it averaged 12.19 μg CO_2-C g^{-1} hr^{-1} (59, 0.50) on West Sedgemoor peats and 14.13 μg CO_2-C g^{-1} hr^{-1} (57, 0.71) on Methwold Fen peats. At 30 ºC it averaged 17.51 μg CO_2-C g^{-1} hr^{-1} (57, 1.07) on West Sedgemoor peats and 15.09 μg CO_2-C g^{-1} hr^{-1} (58, 0.51) on Methwold Fen peats. Unlike Fierer *et al.* (2003a) the addition of glucose increased the rate of C-mineralisation of in all peat horizons relative to basal rates reported in section 7.5.1. Like Fierer *et al.* (2003a) glucose addition at higher temperatures (30 ºC) did enhance respiration in a number of the peats but equally, in a number of cases, a decrease in temperature had the same effect. The trend therefore appears more similar to the basal respiration reported in section 7.5.1 than findings reported by Fierer *et al.* (2003a).

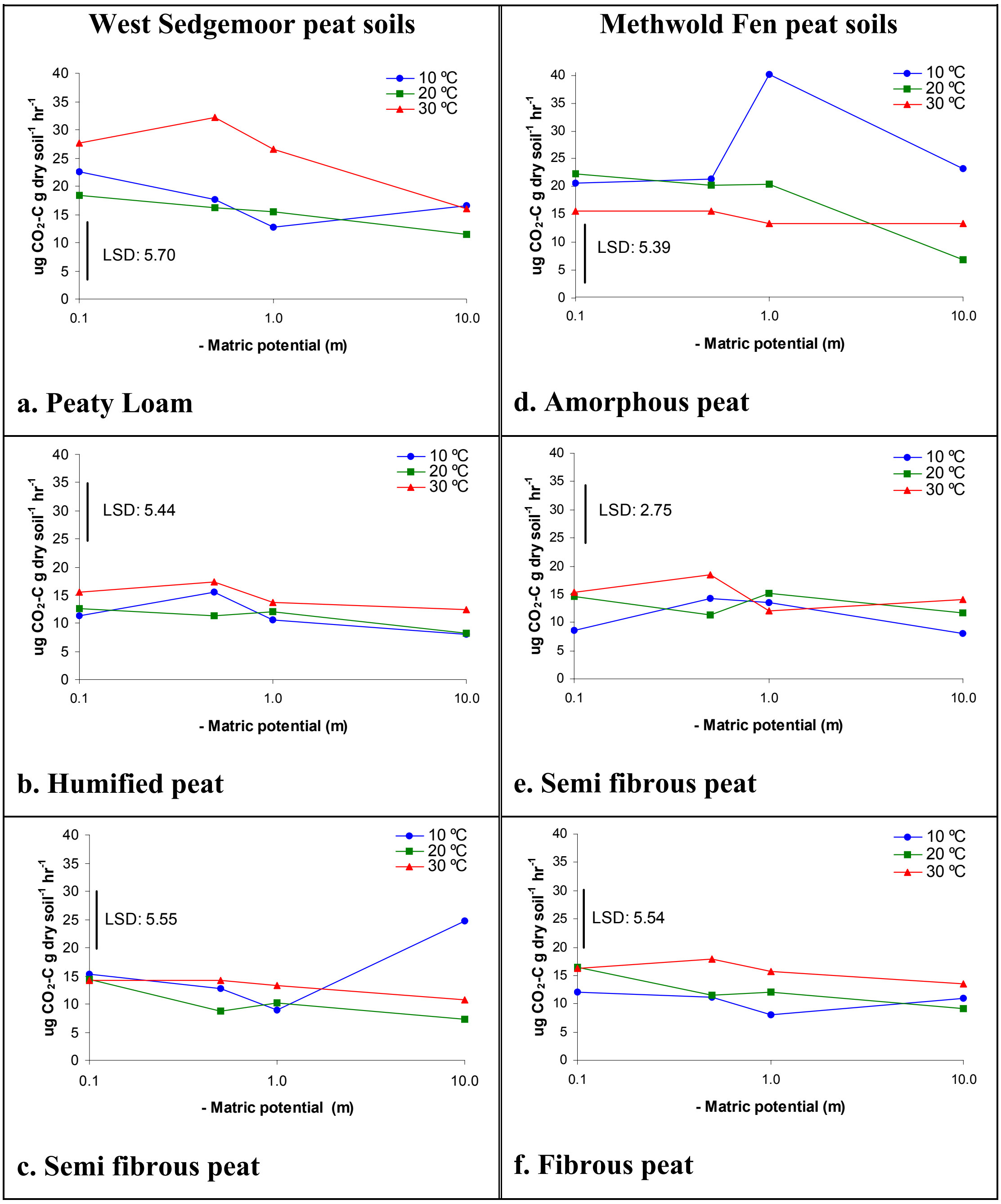


Figure 35: Effect of soil amendment with glucose on soil microbial respiration across a range of pressure potentials and temperatures on peat microcosms from West Sedgemoor and Methwold Fen.

All peats so treated demonstrate elevated respiration rates relative to basal respiration. However, it is more pronounced in the surface peaty loam from West Sedgemoor. The peaty loam also demonstrates a marked increase in respiration with an increase in temperature. The reverse is true in Methwold fen surface amorphous peat, which demonstrates considerably more CO_2-C efflux at 10 ºC when soil moisture is high (corresponding to -0.5 m pressure potential). Generally, in the deeper, more fibrous, horizons such changes in temperature and/or soil moisture content appear to have little effect. However, the deeper semi-fibrous peat from West Sedgemoor does demonstrate greater respiration rate at 10 ºC at lower soil water content corresponding to -10 m pressure potential.

7.5.4. Effects of soil carbon and the C:N ratio on microbial respiration

The availability of carbon and nutrients determines the potential for metabolic activity in the soil. At field scale Heathwaite (1990) found that the degree of water-logging affected the amount of total nitrogen released from the soil. It is possible that the introduction of sub-irrigation systems could bathe underlying peat soils in nutrient-rich waters and that this could increase the rate of biochemical mineralisation of these pristine peats.

Table 9 shows values for SOC content and un-amended soil C:N ratio in the different peats from the different locations. The organic carbon contents are typical for peat soils, comparing with those presented by Burton and Hodgson (1987). Surface soils have lower C:N ratios averaging 12:1 whilst lower peat horizons have a higher C:N ratio averaging 19:1 but with considerable variation; ranging from 13:1 to 28:1. These values are comparable with those reported by Bridgham *et al.* (1998) who reported a range of 14:1 to 38:1 and with Nadelhoffer *et al.* (1991), who reported a range of 15:1 to 27:1.

Source	Peaty type	Soil organic carbon content (%)	C:N ratio
WSM	Peaty loam	18.3 (14, 1.1)	11.3:1 (14, 0.2)
WSM	Humified	37.7 (14, 0.9)	18.5:1 (14, 0.3)
WSM	Semi fibrous	41.7 (11, 1.3)	21.8:1 (11, 1.0)
MF	Amorphous	38.1 (8, 2.2)	14.2:1 (8, 0.6)
MF	Semi-fibrous	41.3 (8, 3.1)	16.1:1 (8, 1.0)
MF	Fibrous	47.4 (8, 0.6)	19.5:1 (8, 0.8)

Table 9: SOC content and C:N ratio of different peats for West Sedgemoor (WSM) and Methwold Fen (MF). Sample size and standard error of the mean are shown in parentheses.

There are no significant differences in C:N ratios between West Sedgemoor and Methwold Fen (p=0.46) but a significant increase in the C:N ratio between surface and sub-surface horizons (LSD: 2.26, p=0.003). It is evident that the surface horizons from both research sites (Amorphous peat and Peaty loam) have much lower C:N ratios than the more fibrous peats. The West Sedgemoor peats underlying the peaty loam soil have the highest C:N ratio and it might be expected that the soil respiration in these lower soil horizons would be most susceptible to increased mineralisation if more Nitrogen was readily available in the soil.

Figure 36 shows plots of changing microbial respiration with amendment of soil C:N ratio and pressure potential. All samples in this study were pre-conditioned by sieving after application of pressure potential and prior to monitoring CO_2-C efflux; hence samples did not retain their volumetric integrity[17]. Therefore, the basal respiration of peat samples reported at 10 ºC in this analysis are not comparable with the basal rates of respiration previously reported. The data does, however, provide a baseline against which to compare C:N ratio amendments. The basal respiration rate averaged 5.9 μg CO_2-C g soil^{-1} hr^{-1} at 10 ºC (72, 0.25), with a range from 1.4 – 10.9 μg CO_2-C g soil^{-1} hr^{-1}, dependent on peat type and pressure potential. Nitrogen additions increase CO_2-C production at all C:N ratios, but is affected by soil moisture.. C:N amended soils average 8.2 μg CO_2-C g soil^{-1} hr^{-1} (210, 0.17), with a range from 1.37 to 16.57 μg CO_2-C g soil^{-1} hr^{-1}. These increases in respiration rate differ to those reported for mineral soils (Fierer *et al.,* 2003b). Fierer *et al*. (2003b) found little effect

[17] In contrast, basal respiration samples were not sieved after applying pressure potential and so could be plotted against soil moisture rather than pressure potential.

of Nitrogen addition in surface horizons but in sub-surface soils the rate of C-mineralisation increased by as much as 450 per cent. The lack of response to nitrogen addition in mineral soils suggests that surface mineral soils are not limited by nitrogen. Conversely, the peats in this work appear able to utilize additional nitrogen whatever there initial C:N ratio.

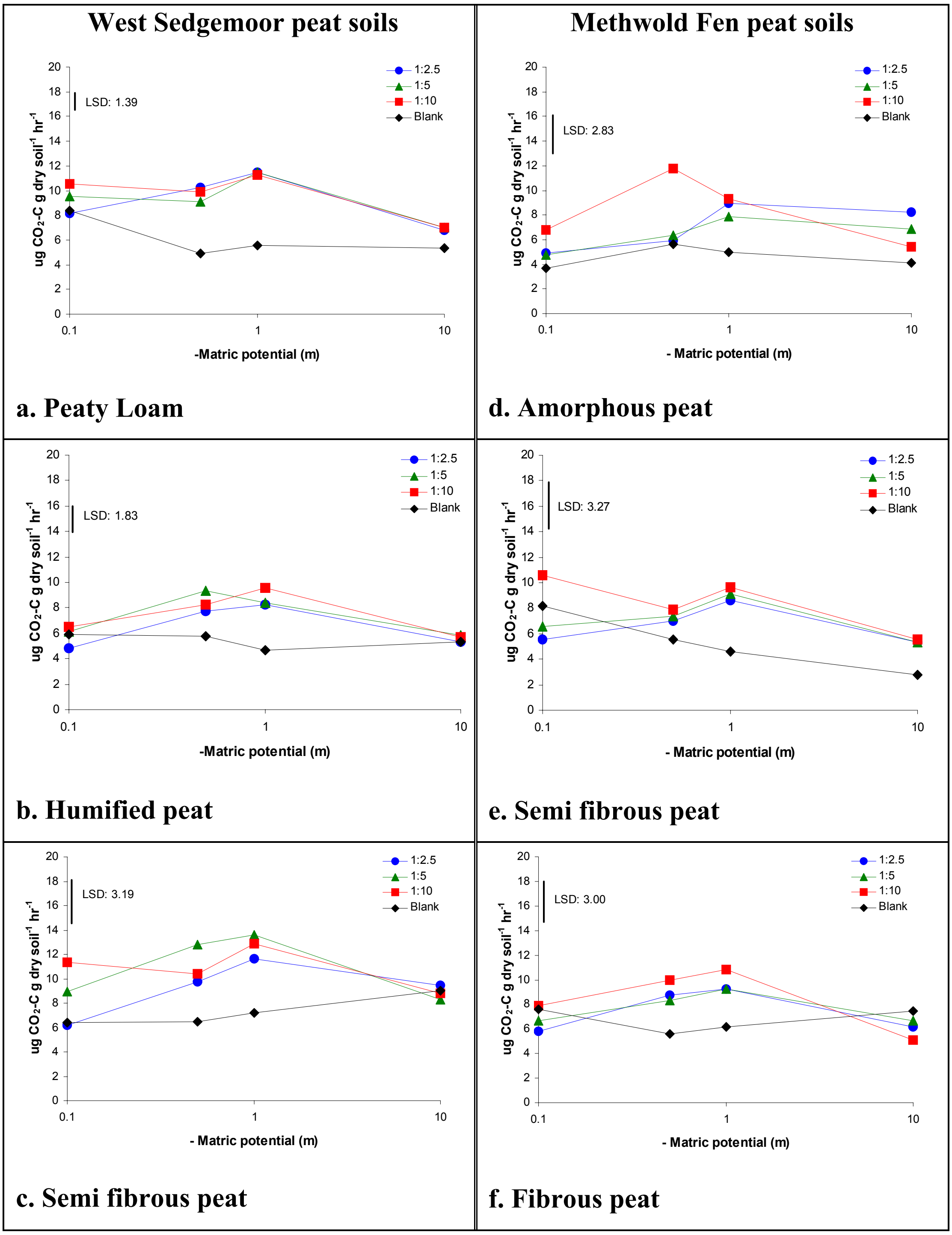


Figure 36: Effect of changing C:N ratio on soil microbial respiration of different peats from West Sedgemoor and Methwold Fen. Plots a-c depict peats at West Sedgemoor and plots d-f show peats from Methwold Fen.

All peats with amended C:N ratios demonstrate considerably greater respiration rates than unamended control samples. There does not, however, appear to be a greater increase in the rate of respiration in those peats that had a higher unamended C:N ratio. Both the surface peats and the deeper, more fibrous, peats from both sites show the greatest enhancement in respiration rate with nitrate addition at -0.5 m pressure potential when compared to basal respiration level, but also have the highest respiration rate without any nitrate amendment.

Contrary to the unamended control samples (where there is no clear pattern in respiratory activity) there are significant increases ($p<0.001$) in respiration with all amended C:N ratios at higher soil moistures (corresponding to -0.1 to -0.5 m pressure potential). At soil moistures equal to or greater than -1.0 m pressure potential five out of six peats show no additional increase in respiration when the C:N ratio is lower than 10:1 (the surface amorphous peat from Methwold Fen shows an increase in respiration with further lowering of the C:N ratio down to 2.5:1 at higher pressure potentials). Generally, the optimal rate of soil respiration occurs when the C:N ratio is 10:1 and the soil moisture corresponds to between -0.5 and -1 m pressure potential.

7.6. Discussion

Although this work didn't investigate the effects of fully saturated soil moisture conditions on microbial respiration, the literature does show that CO_2 emissions from peat is considerably lower under such totally saturated anaerobic conditions (Liu *et al.*, 2002). It is therefore important to recognise that in this micro-scale investigation of respiratory activity that the soil moisture conditions have been under aerobic conditions, as the air entry point of the peat samples under investigation is relatively low (chapter 6.6.3.2).

For the lower end of soil moisture conditions (-10 m pressure potential) the basal respiration rate is higher at higher temperatures. At lower soil moisture content, however, there has not been the conventionally expected Q_{10} increase in the rate respiration between 10 to 20 °C as there has been between 20 to 30 °C. Indeed, the respiration rate at 10 and 20 °C appear quite similar. The 10 and 20 °C experiments better simulate the normal range of temperatures experienced in the field (4 to 20 °C) whereas the 30 °C experiment does not. At low soil moistures the soil microbial community demonstrate a positive reaction to this elevated temperature that suggests a succession in microbial community has occurred. The findings at low soil moisture content are also similar to those reported by Fierer *et al.* (2003a) for mineral soils.

As soil water content increases (corresponding to -0.5m or -0.1m pressure potential) the rate of respiration at 10 °C becomes considerable greater than at either 20 or 30 °C in four of the six peat types. Conversely, the difference in respiration rate between 20 and 30 °C becomes less clear. The marked increase in soil respiration at 10 °C suggests a niche environment optimized by a combination of low temperature and high soil moisture. This is unexpected and suggests the microbial communities at higher soil moistures are specialist, predominantly psychrophilic, microbes as their optimal niche environment is cold (Morita, 1975). This optimal moisture content, which is close to the air entry pressure of these soils, also suggests the microbes are micro-aerophilic (*i.e.* they do require oxygen to operate but do so optimally at very low oxygen concentrations). At West Sedgemoor the deeper peats generally experience almost continual saturation and the annual temperature range in deeper peats also tends to be much lower and narrower (8-4 °C) than those experience in the upper soil horizon (4-20 °C). The results suggest the microbial community in the deeper, wetter peats experience a more adverse effect to temperature stress than those in the upper soil horizons (*i.e.* they operate optimally across a narrow temperature band).

The trend of respiration from Methwold Fen peats is similar from all depths of sampling at greater soil moisture and lower temperature. This suggests psychrophilic microbes predominate in these peats too but also implies that the microbial community is more homogeneously distributed throughout the peat profile. This may be due to the cyclic drainage and irrigation experienced on these intensively managed peats. The microbial activity at these higher soil moistures, though having an unusual temperature response, do seem similar to the optimal soil moisture conditions reported by some authors (Zak *et al.* 1999, Aerts and Ludwig 1997, Chow *et al.* 2006) but contrast with those reported for mineral soils (Stanford and Epstein 1974, Knoepp and Swank 2002) where optimal moisture conditions have been reported as low as

10-35 per cent (volumetric moisture content). Clearly, although pressure potentials are reasonably high in all the peats under investigation, the soil moisture content remains very high. It therefore seems probable that the microbial species at all pressure potentials in peats have adapted to conditions that microbes in mineral soils would find unfavourable.

Microbial respiration efficiency ($qC0_2$) appears greater in the deeper peat horizons at both the conservation site and the intensively farmed site, relative to the surface horizons. However, the difference in microbial efficiency is more marked between the soil horizons at Methwold Fen but of greater magnitude in equivalent horizons of West Sedgemoor peats (Table 9). This suggests the microbial communities in the deeper, more fibrous peat horizons have less available organic carbon for metabolic activities; despite the greater amount of organic carbon in these soils (Table 9). The greater qCO_2 is likely to be due to the more recalcitrant nature of deeper peat horizons (Kanapathy 1976, Maas *et al,* 1979). The effect of a small increase in aeration resulting from a small decrease in moisture content suggests that soil moisture content is a more dominant determinant of peat mineralisation rate than temperature in the initial stages of drainage.

It should be noted that during investigation of respiration from peats amended with glucose or nitrogen that the process of sieving removes any form of peat structure, and that this loss of structure results in the loss of the observed basal respiratory pattern described in section 7.5.1. The loss of such soil structure undoubtedly affects the porosity of different peats to different extents. The granular, unstructured nature of amorphous peat from Methwold Fen suggests it is least likely of all the peats to be affected by such pre-treatment. Indeed, the amorphous peat does appear to be the only soil to retain a similar pattern of increased respiration at lower temperatures and higher soil moistures. Equally though, the results from substrate induced respiration do appear to counter any argument of more efficient microbes in deeper peats responding more vigorously to a more labile carbon pool. Even where there is an increase in respiration in all peats after amendment with an easily metabolised substrate, the addition of glucose does not lead to a more significant increase in respiration of the more fibrous peats. The lack of a temperature response in the substrate amended lower horizons of peats from both sites suggests the lower horizons have retained their generally psychrophilic microbial communities. However, the upper horizons show contrasting responses to substrate amendment.

The different temperature response from the glucose amended peaty loam from West Sedgemoor does point toward a soil that contains a more biodiverse microbial community than deeper peats. A greater variety of microbes in the peaty loam top soil would seems more likely, given that this soil type is prone to other seasonal variations such as the availability of root exudates in the rhizosphere. Conversely, the amorphous peat still shows the same pattern of considerable increase respiration at higher moisture and lower temperature experienced in the basal respiration experiment.

Analysis of the Carbon to Nitrogen ratio (C:N) is a common means of assessing soil fertility and assessing the susceptibility of SOM to oxidisation (Bengtsson *et al.*, 2003). In all cases those peats with nitrogen amendment have greater rates of respiration and a C:N ratio of 10:1 appears to provide the optimal nutrient status. This additional of nitrogen appears to enhance microbial utilisation of the considerable carbon energy source to build new cells from the carbon and nitrogen. However, the findings do not agree with Blagodatsky and Richter (1998), as there does not appear to be a relationship between the carbon pool (degree of peat degradation) and the rate of peat mineralisation when more nitrogen is available. The results demonstrate that all peats respond equally well to the addition of such nitrogen which implies that the carbon pool in deeper, more fibrous peats is equally as recalcitrant as the humified surface peats.

7.7. Conclusions

The greater efficiency of microbial respiration in deeper peats seems such that minimal aeration can have a far more dramatic effect on peat mineralisation than deeper drainage. Basal respiration findings generally suggest that variations in soil moisture can create sub-optimal conditions that reduce the importance of changes in atmospheric temperature. Generally, lower temperature and higher soil moisture or higher temperature and lower soil moisture conditions provide the optimal environmental conditions for microbial metabolic activity in the peat samples studied. This implies that the microbial communities in the peats studied have an optimal operating temperature that coincides with the long-term average soil temperature of 10 ºC, but only if soil moisture remains high. This is in partial agreement with Waksman and Stevens (1929), who reported microbes to be most active above 5 °C. Though such psychrophilic microbes are reported to operate across a broad range of temperatures (0 – 30 ºC) previous research indicates their optimal environment occurs around 5-15 ºC (Morita, 1975). At temperatures greater than 20 ºC there may be a succession in the microbial community, as Roszak and Colwell (1987) report that the mesophilic microbes operate optimally over the range 25–40 ºC.

Soil moisture tends to have a greater effect on respiratory activity at the wetter end and temperature a greater effect at the drier end. Under heavily drained and unusually hot conditions for the UK (*i.e.* 30 °C) respiration is greater, but with minimal drainage and typical UK temperature conditions (10-20 °C) there are equally high respiration rates. The findings imply that unless peats are fully saturated, small falls in a water table (*i.e.* of the order of 10s' of cm) can have a considerable effect on the rate of mineralisation in fibrous peats and such low pressure potentials should be avoided in UK peatlands. Though deeper drainage during cooler periods will reduce mineralisation this latter option is liable to enhance the physical consolidation of peat. Deeper drainage also generates greater spatial variations in soil water content than under shallow drainage during wetting and drying cycles associated with precipitation and high evapo-transpiration. Such deep drainage in conjunction with the frequent wet-dry cycles experienced in the UK is therefore liable to increase the risk of recalcitrant material decomposition in these deeper peats.

Though there are considerable decreases in microbial biomass with increasing depth and pressure potential there are also considerable differences in the efficiency of metabolic activity between the microbes of different peat soils. Although all microbes increase C-mineralisation with an increasingly labile carbon pool and with the addition of nitrogen these 'efficient' microbes do not respond more readily to such nutrient availability than other microbes. This suggests some other parameter(s) are limiting their capacity for enhanced carbon-mineralisation.

One of the most important factors to bear in mind when investigating the effects of soil moisture on microbial respiration is the confounding role that shrinkage can play in quantifying soil moisture conditions. In mineral soil investigations it is often accepted that 60 per cent pore filled space provides the optimal moisture conditions for respiratory activity, but reports of optimal soil moisture do vary. Even without considering such shrinkage the residual volumetric moisture content at PWP for many of the peats studied remains in excess of 40 per cent (section 6.6.3.1). However, at pressure potentials between -1 to -150 m peats often experience loss of pore space equivalent to the volumetric moisture loss (normal shrinkage). If one assumes normal shrinkage, then the change in soil moisture conditions from low to high pressure potentials is not as great as one might expect. Hence where microbial respiratory activity of a fibrous peat is reported optimal at a low pressure potential there may only have been a marginal decrease in the absolute soil moisture content at a higher pressure potential because of shrinkage. This appears to affirm Aerts and Ludwig's (1997) assertion that a relatively small change in water-table height could induce greater CO_2 evolution, but only if one assumes that the change in pressure potential experienced by surface peats is of sufficient magnitude to induce shrinkage in those peats that will return soil moisture to the optimal condition for the resident microbes. It is therefore clear that changes in the rate of shrinkage of different peats at different pressure potentials can complicate quantifying optimal microbial soil moisture conditions throughout the soil profile. Apart from changes in soil moisture, the additional stress that such physical alteration of peat may impose on different microbial communities remains an unknown quantity.

8. Water-table management by sub-irrigation intervention

8.1. Introduction

There are a range of factors influencing how a water table responds to irrigation and drainage intervention:

- Soil physical and hydraulic properties
- Regional climate and surface vegetation cover (evapo-transpiration)
- Water-management practices (control of ditchwater levels)

Chapter 5 considered the total impact on low-lying agricultural peatlands when changes in the water-table regime occur at the macro-scale. Chapter 6 addressed the variation in physical and hydraulic properties of peat soils according to changes in pressure potential that result from fluctuating water-tables. Chapter 7 addressed the micro-scale consequence of variations in soil moisture and temperature on the rate of SOC mineralisation. This chapter is concerned with the influence of climate, land-use and sub-irrigation intervention on large-scale water-management in practice.

8.1.1. Effects of regional climate and land-use on soil water status

The UK Meteorological Office long-term reports (1961-1991) of climate in the UK indicates conspicuous climate differences between the South-Western and East Anglian regions where the peatland research sites are located. The importance of climate data in evaluating regional variations in soil moisture status without any form of water-management intervention is fundamental to investigating soil water management. The UK Meteorological Office generally report that rainfall varies between the South-Western and Eastern regions due to geographic location and surface elevation. Similarly, the climate, surface vegetation type and stage of ‘crop’ growth combine to influence the rate of evapo-transpiration experienced. Quantifying regional variations in rainfall and evapo-transpiration intensity are also crucial for modelling the effect that different sub-irrigation systems will have on water-table dynamics.

8.1.2. Observation and modelling of the water-table under varying sub-irrigation spacings.

The combined effects of ditchwater and sub-irrigation systems on water-table height can be used to optimise water-management practices employed on agricultural peatlands. Chapters 6 and 7 suggest water-table management can reduce physical degradation and biochemical mineralisation of SOM.

Making observations of water-table fluctuation under a range of sub-surface spacings is both expensive and time consuming. Modelling water-table fluctuation can simulate response to such different water-management strategies (*e.g.* Youngs *et al.* 1989, Armstrong 2000). Employing such an approach to agricultural water-management planning allows a greater range of management strategies to be investigated in a shorter time and reduces the financial costs involved in field studies.
WatMod (Leeds-Harrison unpublished) is one such model that allows the effects of varying sub-irrigation spacing be taken into account.

8.2. Contribution to knowledge

Previous studies of water management on peatlands have been primarily concerned with ecological management issues rather than the potential to sustain peat soil resources. The appropriate and timely use of sub-irrigation interventions may enhance the sustainability of agricultural peatlands.

8.3. Aim

To compare and contrast the influence of climate, land-use and water-management practices on the depth of water-table.

8.4. Objectives

- Investigate regional climate data to identify periods of potential soil-moisture deficit where water-management intervention is not employed.
- Monitor the effect of variously spaced sub-irrigation systems on water-table depth.
- Model water-table fluctuation using differently spaced sub-irrigation systems.

8.5. Methods

8.5.1. Climate data analysis

Daily rainfall and potential evapo-transpiration data was provided by the UK Meteorological Office (MORECS) for the 2 year period covering this study (2003/04). The rate of potential evapo-transpiration was calculated by the UK Meteorological Office for each research area using the Penman-Monteith equation (Allen *et al*., 1998) and based on a knowledge of soil type (peat) and typical vegetation cover of the research area (grassland at West Sedgemoor and potato crops at Methwold Fen).

Both West Sedgemoor and Methwold Fen research areas are underlain by Fen Clay (soil survey findings, chapter 5); aiding the assumption that there are no additional gains or losses of water to these soil systems other than by rainfall and evapo-transpiration. MORECS rainfall and potential evapo-transpiration data was therefore analysed to estimate the monthly average soil water balance throughout the year (assuming no water-management intervention). Weekly averaged rainfall and evapo-transpiration data was also used to model water-table fluctuations under changing water-management practices.

8.5.2. Water-table management

At West Sedgemoor sub-irrigation systems were installed using a milling mole plough (Figure 37 a and b). All sub-irrigation systems were installed at 0.7m depth. In all, three different sub-irrigation systems were installed, each in triplicate and each on a separate field. Each sub-irrigation system differed from the next by the spacing between adjacent 'pipes'; which were milled out at 10, 25[18] or 40 m intervals (Figure 38).

a: Cutting blade of a milling mole plough

b: Milled peat extracted from 'pipe'

Figure 37: Implement for creating milled sub-irrigation channels.

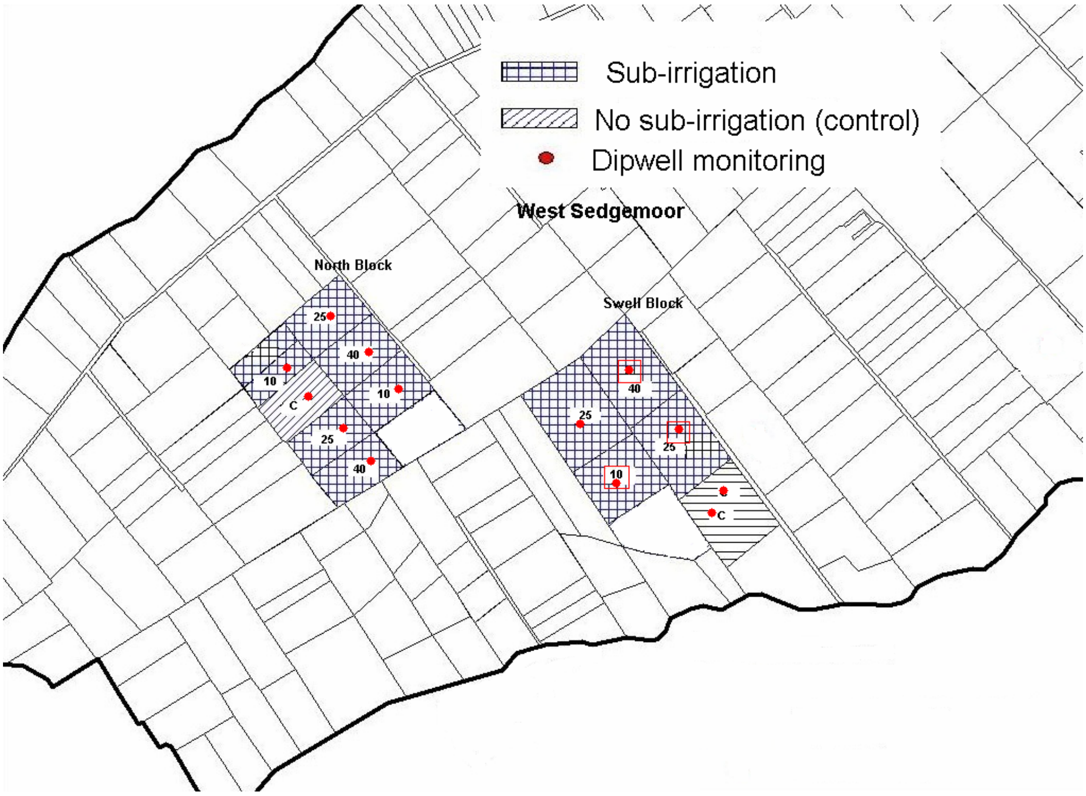


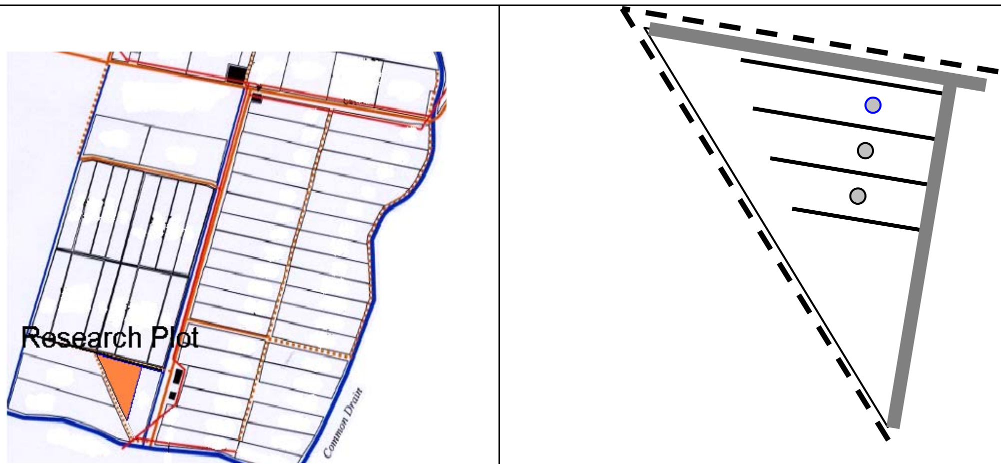
Figure 38: Schematic of West Sedgemoor research fields

At Methwold Fen a sub-irrigation and drainage system of conventional slotted plastic pipes (Figure 39) pre-existed at 20 m spacings across the majority of the farm.

[18] An additional field with 25 m spaced sub-irrigation was installed and is depicted in Figure 38. Data from 1 field was therefore excluded in order to balance statistical analysis of the treatments.

Figure 39: Conventional commercial machinery for installation of slotted plastic pipe.

Prior to installation of the sub-irrigation system at Methwold Fen each field was levelled using land levelling equipment (Hammond, pers comm'). Figure 40a is a schematic of the Eastern part of the Methwold Fen research area which encompasses the detailed study site depicted in Figure 40b.



a: Eastern half of research farm at Methwold Fen, with research field highlighted.

b: Schematic of Methwold Fen research site (black lines denote 20 m spaced sub-irrigation and blue dots dipwells)

Figure 40: Conventional sub-irrigation installation at Methwold Fen.

To monitor changes in field water-table levels at both research sites, dipwells were installed equidistant between adjacent sub-surface drainage / irrigation pipes (Figure 38 and Figure 40b). Water-table and ditchwater levels were recorded at 2 weekly intervals [19]. At both research sites the distance between ditches bounding and supplying water to each field was generally 200 m. All 'control' observation dipwells (those without sub-irrigation installed) at West Sedgemoor were installed sufficiently distant from surrounding ditches to avoid ditchwater levels on control fields having an equal or greater influence on the field water-table level than on fields where sub-irrigation was installed.

8.5.3. Sub-irrigation Modelling

The Ernst-Hooghoudt formulae and the WatMod model (Leeds-Harrison, unpublished) were used to investigate the theoretical impact of regional weather, soil hydraulic properties and water-management strategy on water-table fluctuations of differently spaced sub-irrigation systems. Input parameters for the WatMod model were derived from mean daily potential evapo-transpiration and rainfall data, soil survey of the total peat profile thickness, laboratory calculated saturated hydraulic conductivity of the upper metre of peat (based on a survey of individual horizon thickness); field determined saturated hydraulic conductivity[20] and, finally, the observed ditchwater-management regimes.

The water balance equation used in the WatMod model is a variant of the simple water balance equation given in the literature review, catering for a bounded hydrological regime with sub-irrigation:

[19] Based on observed water-table levels under different sub-irrigation treatments in the field a similar range of water-table levels were instituted on large soil cores collected from each research site and set up in the laboratory (chapter 9.5.2).

[20] The 'slug removal' or Auger-hole method (Appendix C.6) had the benefit of determining the bulk soil profile's hydraulic conductivity without the disturbances often associated with removing samples from discrete soil horizons. However, drawbacks exist with using the auger-hole method because in a heterogeneous layered soil profile the individual soil horizons hydraulic conductivity characteristics cannot be discerned. Similarly, variation in the depth of the water-table between summer and winter mean the season when hydraulic conductivity is determined either includes or precludes surface-horizon contributions to flow. With an appreciation of the drawbacks, an auger-hole test was carried out on each of the 12 research fields at West Sedgemoor through the upper 2.0m of peat.

$$\Delta S = R - ET - q$$

Equation 21: WatMod water balance equation.
where ΔS is the change in storage of water in the system, R is the input due to rainfall, ET is the rate of evapo-transpiration from the system and q is the flow into or out the system by the sub-surface pipes. Change in storage is realised as a change in water-table position in these wet shallow water-table systems.

The Ernst-Hooghoudt model uses all the same input parameters except rainfall data. Such modelling makes the assumption that there are no gains or losses of water to the system due to deep percolation, as both research areas are underlain by an impermeable Fen Clay lower boundary. Lateral boundary conditions (ditches) also allow for the assumption that there are no changes in water balance due to surface run-off losses. Equation 21 implies a steady state condition, where the water table remains fixed. Assuming any change in the storage of the peatland systems is at equilibrium with the water-table level, then any such change in water storage equates to a rise or fall in the water table. This means that all water entering or leaving the system could be considered as a flux through the water table. Youngs *et al.* (1989) state that although a steady state water table does not exist in practice, if one assumes that a series of steady state situations do occur then modelling can be used to solve rises and falls in the water table on a weekly time step. This assumption is also employed in the WatMod model.

In order to quantify such flow into or out of the system through the sub-irrigation/drainage pipe 'q' is considered in terms of the specific yield of the peat and of changes in water-table height with time (Equation 22).

$$q = p \frac{\partial H}{\partial t}$$

Equation 22: Flow equation for losses and gains of water through sub-surface pipes.
where the effective porosity or specific yield of the peat (p) is in $cm^3\ cm^{-3}$, the water-table height above a predefined datum (H) is in metres and time (t) is in days.

Equation 23 presents the rate of such sub-surface flow into the soil system (q) according to Ernst (1975).

$$q = E = \frac{4Km}{L^2}\left[2h_0 + \left(\frac{h_o}{D'}\right)m\right]$$

Equation 23: Ernst (1975) determination of flow into the soil system.

where E is the upward evaporative flux through the water table (in mm d^{-1}) and the saturated hydraulic conductivity (K) is in m d^{-1}. Other parameters are shown in Figure 41.

Solving Equation 23 relies on solution of Hooghoudt's *equivalent depth* (d) given in Equation 24. This theoretical depth to the impermeable boundary below a sub-irrigation pipe is a calibration factor that accounts for the increased entry resistance experienced by water entering a pipe due to the radial shape of the pipe (see Chapter 2.10.3.1).

$$d = \frac{D_0}{\left(\frac{8}{\pi}\frac{D_0}{L}\ell n\frac{D_0}{u}\right) + 1}$$

Equation 24: Hooghoudt's equivalent depth

where the equivalent depth (d) and the actual depth of soil (D_0) are in metres.

However, solution of this theoretical *equivalent depth* relies on solution of the actual pressure head (D') directly over the sub-irrigation pipe, as given in Equation 25.

$$D' = y_0 + D_0$$

Equation 25: actual pressure head above impermeable boundary layer.

where D_0 is the depth to the impermeable boundary below the sub-iirigation pipe; y_0 is the water level immediately over the sub-irrigation pipe and; d is Hooghoudt's *equivalent depth*.

The *equivalent depth* can then be used to calculate the theoretical pressure head (h_0) directly over the sub-irrigation pipe (Equation 26).

$$h_0 = y_0 + d$$

Equation 26: theoretical pressure head above the *equivalent depth* of the impermeable boundary layer.

where y_0 is the height of water level immediately over the sub-irrigation pipe and; d is Hooghoudt's *equivalent depth*.

The simple solution to these parameters is readily apparent by reference to the schematic at Figure 41.

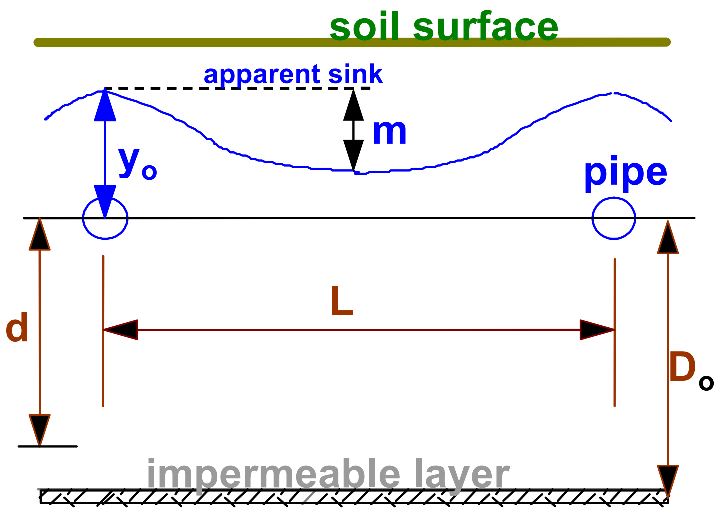


Figure 41: Schematic of data requirements to determine mid-drain water-table level.

where the E is the upward evaporative flux (mm d^{-1}); L is the spacing between adjacent pipes (metres); y_0 is the water table height directly above the sub-surface pipes (metres); D_0 is the actual thickness of soil below the sub-surface pipes to an impermeable boundary (metres); d is the equivalent depth in (metres) and m is the apparent sink in water table midway between adjacent sub-surface pipes (metres).

The Ernst (1975) equation may be re-arrangedto make the drain spacing the subject (Equation 27), allowing the effects of changing sub-irrigation spacing on water table position to be considered.

$$L = \sqrt{\frac{4Km}{ET_0}\left[2h_0 + \left(\frac{h_0}{D'}\right)m\right]}$$

Equation 27: Ernst's apparent sink in water table

where the spacing between adjacent pipes (L) is in metres, saturated hydraulic conductivity (K) is in m d^{-1}, the potential evapo-transpiration ET_0 is in mm d^{-1} and the apparent sink (m) is in metres.

Though the Ernst-Hooghoudt model by itself cannot reflect the likely depth of water table in reality (it lacks a rainfall input parameter), the incorporation of the Ernst Hooghoudt equation into the WatMod Model means changes in soil water storage can better reflect the real water tables of differing sub-irrigation systems. The Ernst-

Hooghoudt model by itself can, however, provide a useful measure of the relative change in water-table position where differently spaced sub-irrigation systems are employed. The Ernst-Hooghoudt model is therefore used in isolation later in this study to elucidate the relative effect of changing sub-irrigation spacing without variations due to rainfall input data.

8.5.3.1. Water-table management on hypothetically co-located peatlands.

The considerable variation in hydraulic conductivity between different peat soils discussed in chapter 6.5.2.2 suggest hydraulic conductivity is determined by the degree of peat humification. To achieve some generic conclusions about different peatlands response to sub-irrigation intervention the Ernst-Hooghoudt equation was used to model some hypothetical peatlands at different stages of degradation (using the mean peat hydraulic conductivity as a proxy for the degree of peatland degradation). All parameters were therefore set equal (according to calculated estimates of climate, land-use and ditchwater management) apart from the averaged hydraulic properties.

8.5.3.2. Modelling considerations

<u>Flow below the phreatic surface</u>

Warrick (2003) asserts that horizontal hydraulic conductivity determines water flow below the phreatic surface. Given that the peatlands under investigation display heterogeneity and anistrophy (due to differential horizontal and vertical soil structure and degrees of degradation), the horizontal saturated hydraulic conductivity was determined using a weighted average of the saturated horizontal hydraulic conductivities of each horizon in the upper metre of peat. This was done according to each horizons specific saturated horizontal hydraulic conductivity and horizon thickness (Equation 28).

$$K_{av} = \frac{(K_1 Z_1 + K_2 Z_2 + K_3 Z_3)}{Z_1 + Z_2 + Z_3}$$

Equation 28: Weighted mean of saturated lateral hydraulic conductivity where $K_1....K_n$ are the hydraulic conductivities of soil horizons in m d^{-1} and $Z_1...Z_n$ are the corresponding horizon thicknesses in metres.

Evapo-transpiration and limiting depth of water table

The rate of evapo-transpiration used in the Ernst-Hooghoudt sub-irrigation equation is a function of the depth of the water table at which evaporation becomes limited. Gardner (1958) defines a soil specific parameter that allows the depth of water table at which the actual upward evaporative flux diverges from the potential upward evaporative flux to be determined. Similarly, Youngs *et al.* (1989) state that the actual evaporative flux of a soil system should be assumed equal to the potential evaporative flux as long as the depth to the water table does not limit the upward capillary flux. Though Youngs *et al*. (1989) suggest a suitable soil specific parameter for peats, this study calculated a soil specific parameter for each peatland according to Equation 29; as long-term differences in water management were known to affect soil physical properties.

$$K(\Psi_m) = K_{sat} e^{(c\Psi)} \quad \text{re-arranged} \quad \mathrm{c} = \frac{1}{-\Psi} \ln\left[\frac{\mathrm{K}\Psi}{\mathrm{K}_{\mathrm{sat}}}\right]$$

Equation 29: The Gardner (1958) solution to unsaturated flow.

where Ksat is the saturated hydraulic conductivity, ψ the (negative) pressure potential $K(\psi)$ the unsaturated hydraulic conductivity at that pressure potential and 'c' the soil specific fitting parameter.

However, to determine the soil specific parameter the mean vertical unsaturated and saturated hydraulic conductivities were required. Vertical flow was determined using a weighted mean of the vertical saturated and unsaturated hydraulic conductivities of each peat horizon in the upper metre of peat, according to horizon thickness (Equation 30).

$$1/K_{av} = \frac{(Z_1/K_1 + Z_2/K_2 + Z_3/K_3)}{(Z_1 + Z_2 + Z_3)}$$

Equation 30: Weighted mean of saturated vertical hydraulic conductivity.

where $K_1....K_n$ are the hydraulic conductivities of soil horizons in m d^{-1} and $Z_1...Z_n$ are the corresponding horizon thicknesses in metres.

The calculated soil specific parameter was substituted into the Gardner and Fireman (1958) equation (Equation 31), to determine the limiting depth of water table and the actual rate of evaporation at depths greater than the critical water-table depth.

$$Z = \frac{1}{c} \ln \left[1 + \frac{K_{sat}}{E_{potential}} \right] \quad \text{re-arranged} \quad E_{lim} = \frac{K_{sat}}{e^{(cZ)} - 1}$$

Equation 31: Gardner and Fireman (1958) equation for determining the depth of water table at which the soil becomes limiting to potential evapo-transpiration.

where the evaporation demands ($E_{potential}$), the actual evaporation (E_{lim}) and the saturated hydraulic conductivity (K_{sat}) have units of m d^{-1}, the depth (Z) is in metres and Gardner's soil specific constant (c) has a unit of m^{-1}.

Hydrostatic pressure below the phreatic surface

Modelling the effect of sub-irrigation on the water-table depth using the WatMod / Ernst-Hooghoudt equations makes the assumption that there are no additional gains and losses of water to the system other than by rainfall, sub-irrigation or evapo-transpiration. The goodness of fit between modelled water-table levels and field observations of different sub-irrigation spacings are compared on West Sedgemoor peats to highlight commonalities and discrepancies between the data sets. To consider gains and losses due to seepage piezometers were installed below each sub-irrigation system to measure hydrostatic pressure potential below the water table. Comparing piezometers installed at different depths provided an indication of potential seepage gains and losses at depth.

- Piezometers were installed at 1.0 m and 2.0 m depths on the three different sub-irrigation treatments at West Sedgemoor.
- Hydrostatic pressure head was monitored at 2-weekly intervals over a six-month period during the late winter to mid summer of 2004/05; spanning inter-seasonal changes in the water-management strategy.

8.6. Results

8.6.1. Regional climate effects on soil-moisture deficit

Weather data (Table 104 and Table 105, appendix G) and soil water balances without water-management intervention are depicted in Figure 42 for West Sedgemoor and in Figure 43 for Methwold Fen. The theoretical soil moisture status is highlighted as the difference between rainfall and evapo-transpiration (ET_0) by a red line.

Analysis of variance of rainfall data over the period 2003/04 (Table 106 to Table 108, appendix G) suggests there were considerable differences in rainfall between months for both West Sedgemoor ($p<0.01$) and Methwold Fen ($p<0.01$) but no overall annual difference in total rainfall between locations ($p=0.70$). Similarly, analysis of evapo-transpiration data indicates there were significant differences in ET_0 rates between months at West Sedgemoor ($p<0.01$) and Methwold Fen ($p<0.01$) but no overall difference in ET_0 between locations ($p=0.069$).

Based on the assumption that there were no additional gains or losses of water to either system statistical analysis suggests there were considerable differences in soil moisture status between each month of the year at West Sedgemoor ($p<0.01$) and Methwold Fen ($p<0.01$). However, there were no overall differences between locations each month ($p=0.60$) or between locations each year ($p=0.99$).

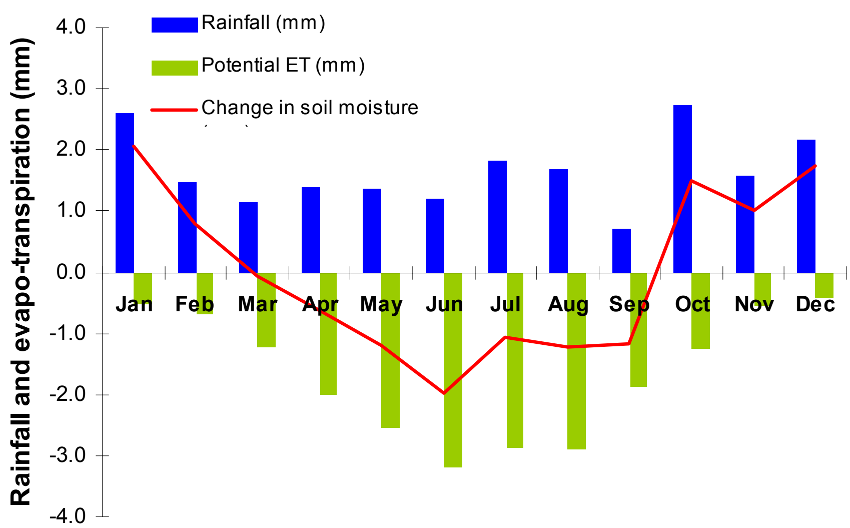


Figure 42: West Sedgemoor averaged daily meteorological data (for each month) for 2003/2004 (based on grass crop).

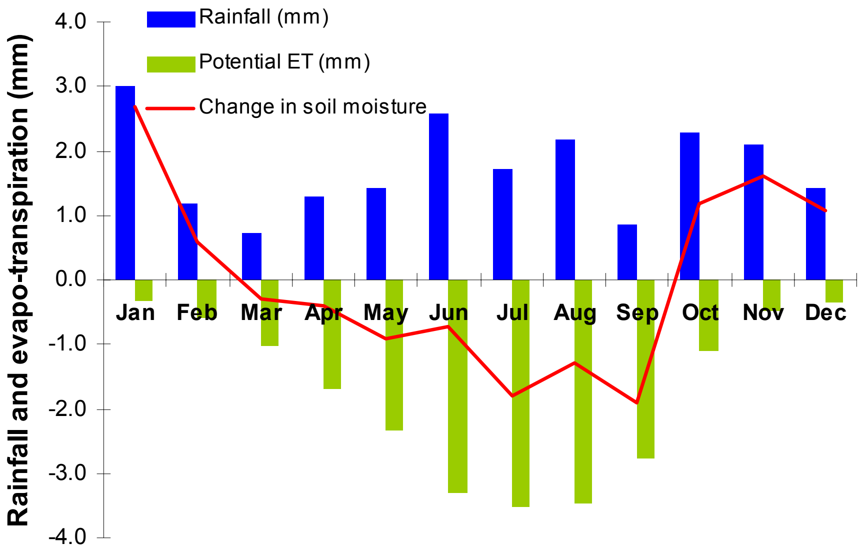


Figure 43: Methwold Fen averaged daily meteorological data (for each month) for 2003/2004 (based on potato crop).

8.6.2. Observed water-table positions

8.6.2.1. West Sedgemoor.

During the period January to December 2003 the water-management regime for West Sedgemoor was in accordance with the Tier 3 water-management regime (*i.e.* held at mean field level during the period November to April and at 0.3 m below mean field level during the period April to October). The calculated change in water levels between supply ditches and the mid-points between adjacent sub-irrigation pipes for each sub-irrigation system (Control, 10, 25 and 40 m spacings) are given in Figure 44[21].

[21] This method of reporting was used in preference to reporting individual values for the height of field water level and the height of the ditch water level in each field system. This allowed the effect of changing surface elevation between different fields to be discounted and hence statistical analyses could be applied to the change in water levels on multiple fields with the same treatment but different surface elevation.

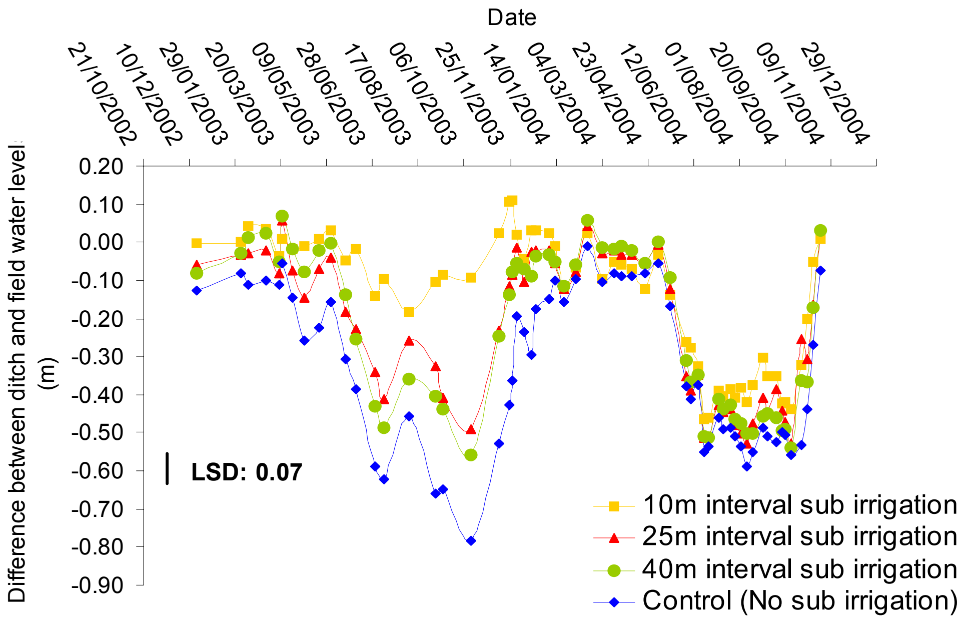


Figure 44: Observed difference in water-table depth between ditches and fields under 3 different sub-irrigation spacings and a control with no sub-irrigation on West Sedgemoor.

During the summer of the 2003, when the ditchwater levels were maintained at 0.3 m below mean field level, those fields surrounded by ditches at 200 m spacing (Controls) had a water table greater than 1.0 m below the mean field surface. This meant the fall in water level from the ditch system to the mid-field point averaged 0.75 m. Where sub-irrigation pipes were at 10 m spacing the field water table was, at maximum, 0.4 m below mean field level and hence there was at maximum only a 0.1 m fall in water level from the ditches to the associated mid-field dipwells. The results compare well with Hooker (1991).

During 2003 the change in water-table level on 10 m spaced sub-irrigation systems was minimal (Table 110, appendix 283) relative to 25, 40 m or no sub-irrigation ($p<0.001$). Where no sub-irrigation was employed the fall in water table was significantly greater during the summer than sub-irrigation systems at 25 or 40 m spacings ($p<0.001$). The difference in water table between 25 and 40 m spaced systems was too variable to be considered significant (LSD 0.07 m). During the summer of 2004 the difference in water table between ditch and field for all spacings converged; with 10 m spaced systems decreasing in efficiency and all other sub-irrigation spacings increasing in efficiency. Figure 44 demonstrates there were no appreciable differences in water-table depth during the second year of investigation (LSD: 0.07).

8.6.2.2. Methwold Fen.

A smaller scale monitoring exercise was instigated at Methwold Fen during the period January to July 2005. In general the water-management regime consisted of top-irrigation during the early spring months to develop crop root systems. In late spring the ditchwater level was raised to 0.5 m below mean field level to provide sub-irrigation throughout the rest of the summer. In late autumn/early winter ditches were completely drained to improve land access for maintenance operations. The difference in water level between ditch and field is summarised in Figure 45.

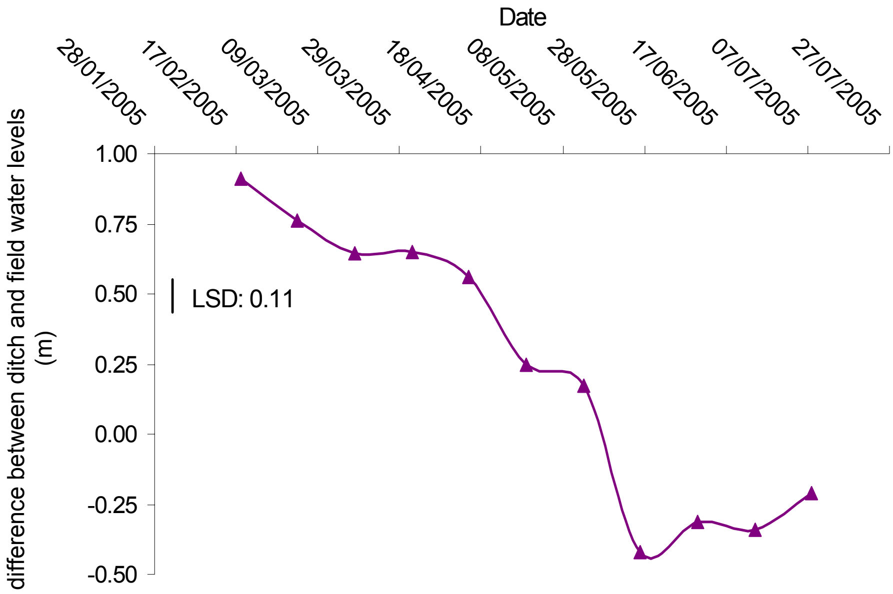


Figure 45: Difference between ditch and field water levels on 20 m spaced system at Methwold Fen.

The findings (Table 111, appendix H) depicted in Figure 45 indicate that the research site remains highly saturated during the winter and spring months, irrespective of the ditch system drainage to between 1.0 and 1.4 m below mean field level (*i.e.* below the depth of the sub-surface pipe system). After raising the ditchwater-level to between 0.45 and 0.55 m below mean field level (*i.e.* 0.15 to 0.25 m above the sub-irrigation pipe system) the difference in water level between ditch and field is only 0.2 m. Analysis of variance (Table 112 and Table 113, appendix H.1) indicates there is no difference in the change in water-table level at any time in between the 3 dipwells under observation ($p=0.97$) but that there are considerable changes between ditch and field water levels when the sub-surface system switches from drainage during the winter to irrigation during the spring and early summer ($p<0.001$).

8.6.3. Modelled changes in water table under varied sub-irrigation spacing, environmental conditions and water-management practices using the WatMod model.

For West Sedgemoor the variations in rainfall and ET_0 during 2003/2004 are considered in section 8.6.1. Due to contractual constraints meteorological data provided by the UK Meteorological Office for modelling Methwold Fen water-table response during 2005 cannot be published in this document.

For the peatland at West Sedgemoor the WatMod determined response of the water table to variously spaced sub-irrigation systems are plotted in Figure 46. Figure 46a is for 10 m spaced sub-irrigation; Figure 46b is 25 m spacing; Figure 46c is for 40 m spacing and Figure 46d is the control with no sub-irrigation (200 m spaced ditches). The observed data used for comparison with modelled data is presented in section 8.6.2.1. Modelled water-table responses are based on the soil hydraulic conductivity data presented in chapter 6.5.3.4[22]. From such data the mean saturated hydraulic conductivity in the upper metre of peat was estimated to be 1.77 m d^{-1} (Equation 40 Appendix E). However the field-derived average saturated hydraulic conductivity in the upper 2.0 m of peat (16 separate auger hole tests - appendix C), was considerably lower; at 0.81 m d^{-1} (Table 67, appendix E). The saturated vertical hydraulic conductivity was 0.21 m d^{-1} (Equation 41 appendix E) and the unsaturated vertical hydraulic conductivity at 1.0 m pressure head was 3.5×10^{-3} m d^{-1} (Equation 44 appendix E.11). The specific yield calculated at 1.0 m pressure head (Hillel, 1998) in chapter 6.6.3.4 was 0.18 cm^3 cm^{-3} and compares with that reported by Parkin *et al.* (2004).

[22] The unsaturated hydraulic conductivity used in Gardner's (1958) equations was calculated on the basis of soil survey data of peat horizon thickness in the upper metre of soil and on the lowest observed water-table depth during the period of research in 2003. This enabled a theoretical weighted mean for the vertical saturated and unsaturated hydraulic conductivity to be estimated in the upper metre of soil, based on a weighted pressure potential at the mid-point of each soil horizon.

The actual thickness of peat deposit used in modelling water tables at West Sedgemoor was 5.25 m (chapter 5.5.2). Coincidentally, the soil specific parameter was 5.25 m^{-1} (Equation 46, appendix H), which compares well with that of Youngs *et al.* (1989). The limiting rate of evaporation was 14 mm d^{-1} (Equation 48, appendix H) and the water-table depth at which the rate of evaporation becomes limited was 0.72 m (Equation 47, appendix H). All the above parameters are used in the WatMod modelling of the effect of sub-irrigation depicted in Figure 46. In all simulations WatMod calculation shows agreement with observed data; that a decrease in water-table position occurs with changing season and with increases in the distance between adjacent sub-irrigation systems.

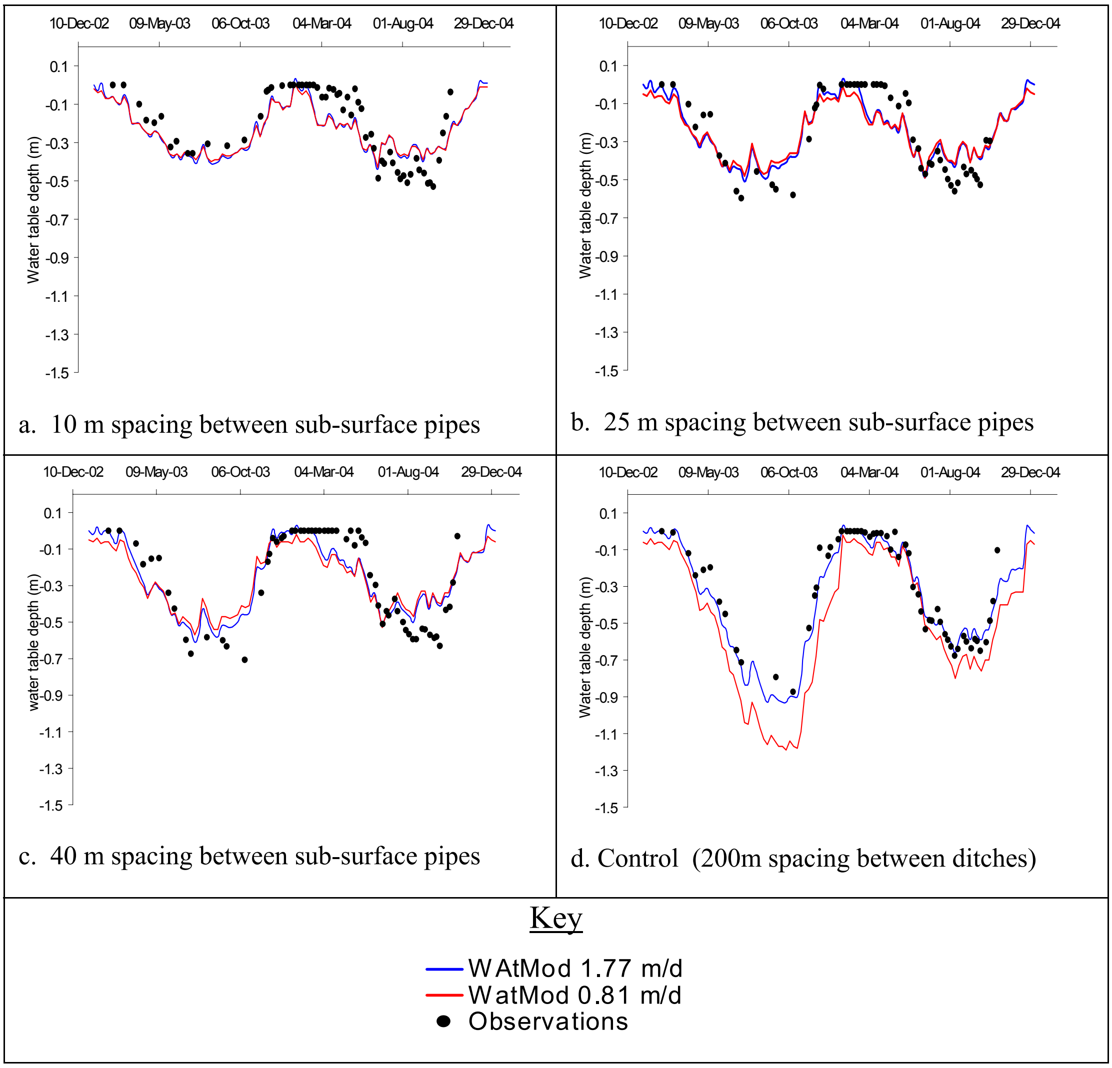


Figure 46: Comparison of WatMod modelled water-table depth against observed data for differently spaced sub-irrigation systems at West Sedgemoor.

The WatMod model has a strong correlation with observed data for all sub-irrigation system spacings (mean R^2=0.81); though the goodness of fit does reduce as the sub-surface spacing decreases (Figure 47) the modelling efficiency remains very good with all sub-irrigation system spacings[23].

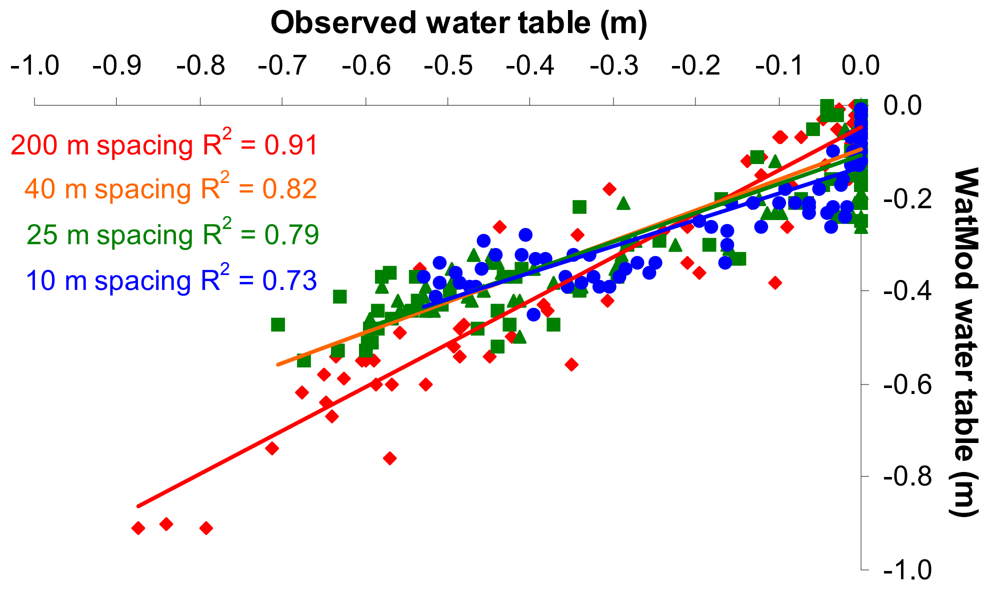


Figure 47: Correlation between WatMod and observed water-table data.

The WatMod model was fairly insensitive to the difference between laboratory calculated and field derived saturated hydraulic conductivity. Whilst there were minor discrepancies in the goodness of fit between the field derived and laboratory calculated hydraulic conductivity values, on fields where only ditchwater management was employed (Controls) the laboratory calculated saturated hydraulic conductivity provided the better fit. WatMod was more responsive to changes in the specific yield than to hydraulic conductivity.

The analysis of differences in hydrostatic pressure head below the sub-irrigation systems (between 1.0 and 2.0 m depth) suggest that there were very small fluctuations in both upward and downward flow (Table 119, appendix H) but the reasonably good

[23] The WATMOD modelling efficiencies (Smith *et al.*, 1996) were 0.90 (200 m intervals); 0.79 (40 m intervals); 0.75 (25 m intervals) and; 0.65 (10 m intervals).

fit between modelled and observed data suggests such seepages were too small to influence water-table levels.

For the peatland at Methwold Fen the WatMod modelled response of the water table to 20 m spaced sub-irrigation is plotted in Figure 48. The observed data used for comparison is that presented in section 8.6.2.2. Modelled water-table responses are based on hydraulic conductivity data presented in chapter 6.5.3.4. From such data the mean saturated hydraulic conductivity in the upper metre of peat was estimated to be 1.48 m d^{-1} (Equation 42, appendix E). The saturated vertical hydraulic conductivity was 0.25 m d^{-1} (Equation 43, appendix E.11) and the unsaturated vertical hydraulic conductivity at 1.0 m pressure head was 1.27×10^{-4} m d^{-1} (Equation 45, appendix E.11). The specific yield calculated at -1.0 m pressure head (Hillel, 1998) in chapter 6.6.3.4 was 0.22 cm^3 cm^{-3}. The mean thickness of peat deposit at Methwold Fen was 1.28 m (chapter 5.5.2). The soil specific parameter was considerably higher than West Sedgemoor peats, measuring 10.11 m^{-1} (Equation 49, Appendix H). The limiting rate of evaporation was 1.6 mm d^{-1} (Equation 51, appendix H) and the water-table depth at which evaporation becomes limiting was 0.41 m (Equation 50, appendix H). Entry resistance to the slotted plastic pipes was used as a fitting parameter and 0.25 m entry resistance provided the best fit.

There were very small differences in hydrostatic pressure head below the sub-surface system, which indicated a small amount of upward and downward flow (Table 120, appendix H). These seepages were, however, so small that they were not believed to have a significant impact on water-table management.

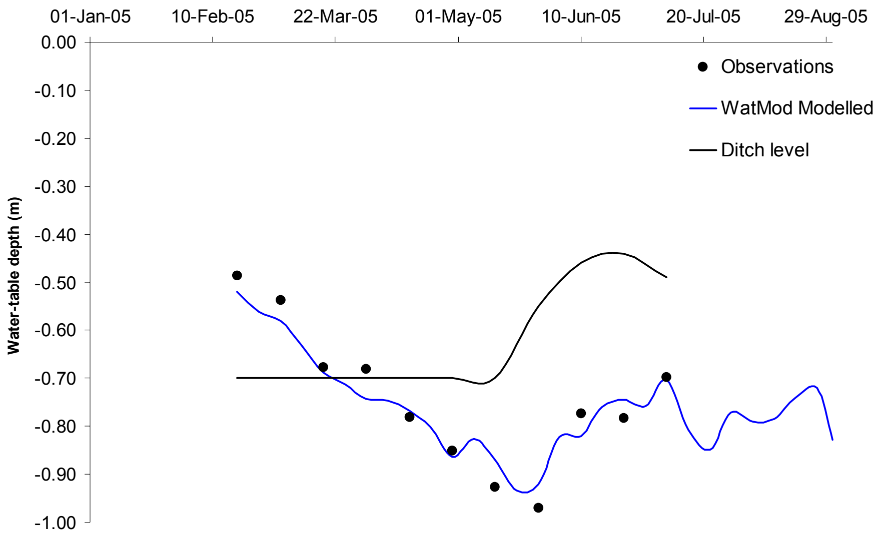


Figure 48: Comparison of WatMod modelled water-table depth against observed data for 20 m spaced sub-irrigation systems and ditchwater level at Methwold Fen.

The limited extent of the study at Methwold Fen precluded a long enough data set being collected for a reasonable comparison between the WatMod modelled and observed water tables. It was the presence of ochre in sub-surface pipes that necessitated an adjustment to entry resistance to the pipe. This resulted in a good fit that demonstrated the effect of the sub-surface system when the ditchwater level was raised above the sub-surface pipe systems during the late spring.

8.6.3.1. Modelling the relative effect of a wide range sub-irrigation spacing on the water-table level

To assess the relative effect of different sub-irrigation systems on water-table depth the following analyses consider the hypothetical differences in water-table without variable rainfall inputs. The analyses rely on the Ernst-Hooghoudt formula alone. The Ernst-Hooghoudt model by itself assumes no gains or losses of water to the soil system other than by sub-irrigation and evapo-transpiration. This limitation therefore provides an indication of the relative effects of changing sub-irrigation spacing alone on water-table depth; by removing variations due to rainfall.

A series of sub-irrigation systems between 5 and 200 m spacings are depicted in Figure 49. The results do suggest that to maintain a water-table level at Methwold Fen similar to that at West Sedgemoor would require a considerably different water-management strategy at Methwold Fen. Simulations are based on peat physical properties, climate and water management defined in section 8.6.3 above.

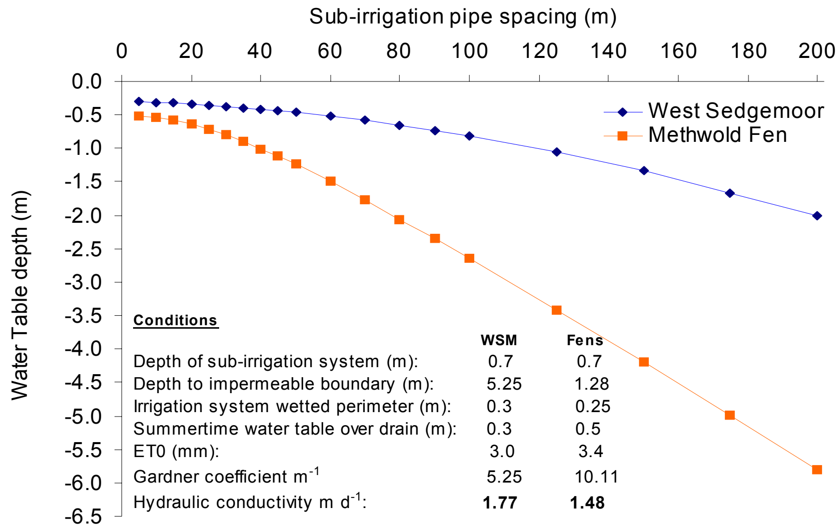


Figure 49: Modelled water-table depth at West Sedgemoor and Methwold Fen using different sub-irrigation spacing

The considerable variation in saturated hydraulic conductivity determined within and between research sites (chapter 6.5.2.2) suggests a relationship between the degree of peat degradation and the ability of water to move through the soil. To assess the large-scale effects of such variation in degradation alone required a hypothetical situation to be considered. The analysis of the sole effect of peat degradation is depicted in Figure 50.

The weighted, laboratory calculated, hydraulic conductivity of the upper metre of peat used in this hypothetical modelling work was the sole parameter that differentiated between West Sedgemoor and Methwold Fen peats. All parameters other than hydraulic conductivity and the soil specific parameter were set equal (*i.e.* discounting the effects of peat thickness, regional climate and vegetation cover). The thickness of peat deposit to the impermeable clay boundary was 3.75 m (the average thickness of peat deposit calculated from both research sites); the daily summertime ET_0 was 3.2 mm d^{-1} (calculated from the mean summertime ET_0 from both regions between June to August 2003-4); the depth of sub-irrigation system was 0.7 m and the depth of summertime ditchwater level was 0.4 m (median summertime value from both research sites).

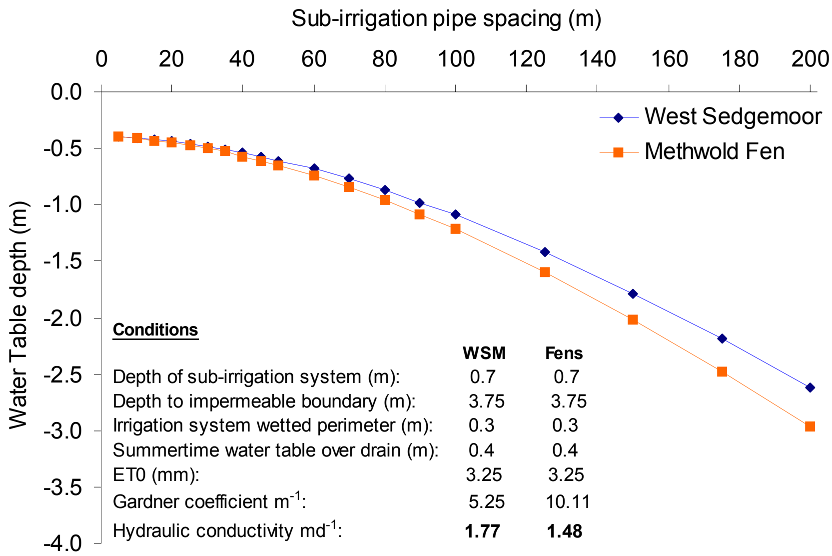


Figure 50: Ernst-Hooghoudt modelled assessment of the water-table response to peatlands of differing degradation but similar peat deposit thickness and environmental conditions (based on differing saturated hydraulic conductivity determined for West Sedgemoor and Methwold Fen peatlands).

The findings demonstrate that the water-management strategy would change considerably if peatlands similar to West Sedgemoor and Methwold Fen were considered in a hypothetically co-located setting, where the only factor affecting water-table management was the degree of peat degradation (K_{sat}).

Where the rate of evapo-transpiration and the water-management strategy are similar and peat deposits are of equal thickness but of historically different land-use (and hence degree of degradation) there is very little difference in the water-table level across a wide range of sub-irrigation systems of differing degree of degradation. Comparison of Figure 49 and Figure 50 suggests that the thickness of peat deposit to the impermeable boundary is the major factor influencing water-table depth. Modelling the above scenario across a range of peat thicknesses (Figure 51) demonstrates that where only ditchwater levels are controlled there must be a considerable peat deposit (>5.0 m) if the underlying impermeable boundary is not to influence flow-lines from sub-surface pipes and hence water-table levels. Where sub-irrigation systems have been employed to enhance water-table levels the minimum thickness of peat deposit required to ensure a reasonable water-table response to the sub-irrigation system is considerably less; with an estimated critical minimum thickness to the impermeable boundary of 1.75 m.

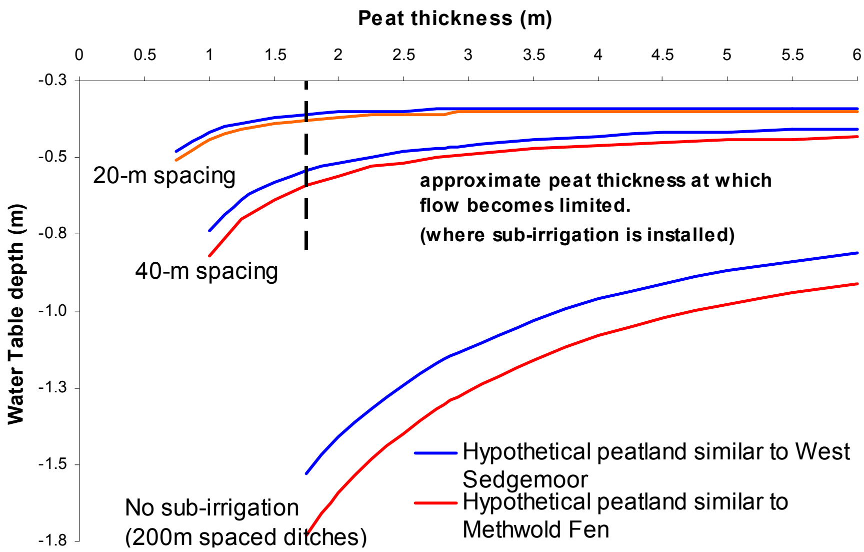


Figure 51: The effect of modelling different peat deposit thicknesses using the Ernst-Hooghoudt equation.

8.7. Discussion

8.7.1. Soil water balance without water management

Over the period of 2003-04 the estimated soil water balance without water-management intervention, for both research sites, were unusual because the long-term reports by the UK Meteorological Office (1961-1990) suggest the Anglian region (especially around the Methwold Fen research area) has historically been much drier than the South-Western (Somerset Levels and Moors) area.

During the 2003-04 period of field research it was quite dry across the whole UK and, irrespective of regional similarities in rainfall and evapo-transpiration data, the calculated soil water balance suggests both sites have the potential for a soil water deficit (without water-management intervention) during the period March to September. If such an annual soil-moisture deficit occurred over the longer-term the potential exists for a drop in the water table and an associated increase in the depth of vadose zone. This would lead to greater pressure potentials being experienced in the vadose zone and the likelihood of increased shrinkage, consolidation and biochemical mineralisation of deeper peats.

8.7.2. Water-table management

Where sub-irrigation is employed in conjunction with ditchwater management at West Sedgemoor the observed changes in water-table levels suggest that during the summer months' sub-irrigation systems with equal to or less than 25 m spacing provide the most detailed control of the field water table. 10 m spaced sub-irrigation systems enhance control of the field water-table level even further, with results indicating that the field water-table level will mirror the penning level in the supply ditch. However, the effectiveness of sub-irrigation at these spacings is ultimately reliant on appropriate ditchwater management remaining in place. Though the performance of the sub-irrigation systems during 2003 demonstrate the feasibility of milled out sub-irrigation pipes over the short-term, observed water-table levels during 2004 suggest that milled sub-irrigation may suffer practical problems of pipe blockage. Such water-table control may also be affected by seepage into/out of the individual soil systems but this did not occur during this study. Whilst installation of more conventional plastic slotted pipes may reduce such collapse and/or blockage, more frequent cleaning of supply ditches may improve the longer-term viability of milled channels.

The sub-surface system at Methwold Fen (in theory) acts as both a drainage and sub-irrigation system. The high field water-table level observed during the winter of 2004-05 did fall gradually with the approach of spring, but generally the sub-surface system appears ineffectual at draining the fields during the winter. Such slow rates of drainage are likely to be exacerbated by ochre partially blocking the slotted plastic pipes; causing increased entry and exit resistance to/from the slotted pipes. Ochre results from the presence of Fen Clay and the shallowness of peat deposit below the sub-irrigation system. Over and above this, the difference in water level between ditch and field on these 20 m spaced sub-irrigation systems appears quite similar to the 25 m spaced sub-irrigation system of West Sedgemoor. Given the greater (and fluctuating) ditch pressure head at Methwold Fen it even appears that the sub-irrigation system at Methwold Fen functioned marginally better than the 25 m spaced system at West Sedgemoor. This may be due to the shallower depth of peat deposit to the impermeable clay horizon at Methwold Fen. With an appreciation of the soil hydraulic properties of individual peat horizons the findings suggest that the lack of drainage in the upper amorphous peat horizon at Methwold Fen may be due to the poor vertical hydraulic conductivity of the upper amorphous plough layer (0.24 m d^{-1}). However, when the sub-irrigation system becomes active during the late spring the position of the sub-irrigation system in the lower semi-fibrous peat layer (which has a saturated horizontal hydraulic conductivity of 2.12 m d^{-1}) may enhance the effectiveness of the sub-irrigation system. The location of the sub-surface system in the semi-fibrous peat horizon may provide an additional explanation of why the 20 m spaced system at Methwold Fen appears to perform better than the 25 m spaced system at West Sedgemoor, which is situated in more humified peat that has a lower horizontal saturated hydraulic conductivity of 1.55 m d^{-1}.

In terms of water-table modelling, the large difference in saturated hydraulic conductivity between field derived and laboratory calculated values of the West Sedgemoor peatland demonstrates the difficulty in estimating this parameter for peatlands. The findings suggest that determining field saturated hydraulic conductivity with an auger hole test during summer months can lead to under-estimation of hydraulic conductivity; possibly because flow in surface horizons above the water table are not incorporated into the derived value. Between research sites, the mean weighted, laboratory determined saturated hydraulic conductivity of the West Sedgemoor peatland appears to be slightly greater than that calculated for the Methwold Fen peatland. This might seem out of keeping because in the upper metre of peat the West Sedgemoor peatlands tend to be slightly more degraded than Methwold Fen peats (excepting the surface amorphous peat at Methwold Fen). This difference probably occurs because of the greater consolidation experienced by the deeper, fibrous peats at Methwold Fen.

Given the water-management strategy and observed water-table data for West Sedgemoor, the soil specific parameter indicates that the actual rate of evaporation is unlikely to be limited by water-table depth. Even though the water table falls marginally below this critical threshold on fields without sub-irrigation the limiting rate of evaporation is high enough that it is unlikely to affect the actual rate of evapo-transpiration.

For Methwold Fen the commonly employed summer time field water table of 0.5 m below mean field level is deeper than the limiting depth at which evaporation becomes limited by the depth of the water table (0.41 m). It appears that the evaporation component of ET_0 would therefore be decreased during summer months to a maximum rate of 1.6 mm d^{-1}. Whilst this limitation to the actual rate of evaporation may cause surface soil horizons to dry out, the water table would tend to flatten out because of the eventual reduction in surface losses of water. This may reduce the sum total of evapo-transpiration but the rate of transpiration from deep rooting crops would remain unaffected. During the winter months the observed water-table depths suggest that evaporation would be unlikely to be limited by the depth of water-table because of the poor drainage system.

When modelling the effects of sub-irrigation with WatMod the difference in hydraulic conductivity values does not appear to have an appreciable effect; though for West Sedgemoor the laboratory determined hydraulic conductivity does provide a marginally better fit across a wider range of observed data.

Using the Ernst-Hooghoudt model to assess the sole importance of sub-irrigation spacing on the apparent sink does suggest that even though the weighted mean hydraulic conductivity values for each site are not that different, the effects of regional climate, peat thickness and land-use all combine to demand a more closely spaced sub-irrigation system on peatlands of similar land-use to Methwold Fen. However, where the hypothetical situation of co-located peatlands of similar peat thickness, but different historical land-use, is considered, the outcome suggests the degree of peatland degradation is not a major factor.

If the thickness of peat deposit in these hypothetical peatlands diminishes then the differently spaced sub-irrigation systems respond quite differently and there is a dramatic change in water-table response beyond a critical threshold of 1.75 m. This implies that the most important factor governing sub-irrigation modelling in the Ernst-Hooghoudt equation is the thickness of peat deposit to the underlying impermeable soil horizon. This is not to say that sub-irrigation is not viable in shallow peat deposits, but purely that the thickness of peat deposit does limit the potential pressure head above the sub-irrigation system (if one assumes underlying impermeable boundary conditions). The thickness of peat deposit at Methwold Fen does, though, point toward decreased efficiency of the sub-irrigation system; with the shallow peat deposit hampering drainage during the winter months. Equally, however, this may reduce aerobic microbial mineralisation of SOM.

8.8. Conclusions

Regional climate and land-use are generally accepted as the major factors governing soil moisture status without irrigation intervention. The small amount of weather data used in this work does not highlight such regional differences and therefore does not enable appreciation of the importance of regional climate on soil moisture status to be assessed but it does highlight that there are seasonal soil-moisture deficits that over the longer-term could exacerbate the rate of peatland degradation and loss.

Observation of water-table levels under differing sub-irrigation system spacing demonstrates that employing such a water-table management strategy can provide a viable means of enhancing the soil water balance throughout drier summer months. However the effectiveness of the system is dependent on its appropriate design and on maintaining the designated ditchwater management regime. Generally, where sub-irrigation is spaced at 10 m intervals then the water table approximates to the ditchwater level. However, the longer-term efficiency of milled out sub-irrigation tiles is questionable and a cost-benefit analysis may indicate that using slotted plastic pipes is a better long-term economic investment. Where the sub-surface system is also used for drainage its effectiveness can be hampered if the rate of vertical flow through the peat is low. Equally, the effectiveness of such a sub-surface system for irrigation purposes can be affected by a combination of the thickness of peat deposit to any underlying impermeable boundary and the type of peat horizon in which the system is installed. The critical thickness of peat deposit at which the efficiency of sub-irrigation is dramatically reduced occurs around 1.75 m. The presence of ochre in sub-surface pipes can have a direct and considerable influence on the efficiency of both drainage and sub-irrigation systems. The initial discrepancy between observed and modelled data from Methwold Fen demonstrates that there can be a loss of up to 0.25 m pressure head if slotted plastic pipes are not regularly unblocked. Such water jetting of sub-irrigation pipes can restore lines to original efficiency, but commercially available high pressure hose systems operating between 40-100 bar are expensive to hire. This suggests there may be longer term cost benefits to installing a milled set of sub-surface ‘pipes’.

The design of such sub-irrigation requires a sound knowledge of regional climate; the proposed land-use (rate of evapo-transpiration); water-management strategy; thickness of peat deposit and analyses of soil hydraulic properties. Even where such a detailed inventory of the peatlands characteristics have been determined the results suggest that such sub-irrigation design can benefit from a degree of over-engineering to cater for the highly variable hydraulic properties of the soil and the propensity of such properties to diminish over time as the peat degrades. With such knowledge the water-table response to varying sub-irrigation spacing can be easily modelled using empirical water-balance models such as WatMod. The good agreement between WatMod and observed water-table data demonstrates that such modelling allows the effectiveness of such sub-irrigation systems to be evaluated prior to undertaking any real works. Importantly, modelling a set of theoretical peatlands of differing degradation status demonstrates that, assuming all things are equal apart from degradation state, such peatlands would both respond favourably to very similar water-management strategies if they were subject to similar land-use and water-management regimes. But again, modelling demonstrates that the thickness of peat deposit can have dramatic effects on the efficiency of sub-irrigation.

Given the feasibility of enhanced water-table management using sub-irrigation, the consequence of such management practices on large-scale mineralisation of soil organic matter are considered in chapter 9.

9. The consequence of large-scale water management on the microbial community structure and mineralisation rates of soil organic matter.

9.1. Introduction

Chapter 7 considered the micro-scale consequence of soil water content on SOM mineralisation whilst chapter 8 dealt with the feasibility of larger-scale soil water management. This chapter considers the consequence of such larger-scale water management practices on below surface respiration, organic matter mineralisation and microbial community structure.

9.1.1. Field-scale monitoring of below surface respiration

The study of peat microcosm mineralisation rates under different soil moisture content and temperature regimes enables quantification of the small-scale contribution of these variables to SOM mineralisation (chapter 7). At larger scales Best and Jacobs (1997) and Liikanen *et al.* (2005) affirm that differences in soil moisture and atmospheric temperature are dictated by seasonal and regional variations in climate and water-management practices. Whilst previous research of SOM mineralisation rates at the field-scale indicates that such mineralisation rates are seasonal such work also suggests it is highly variable (Inubushi *et al.*, 2003). The larger-scale effects of water-management practices and seasonal variations in climate therefore need to be investigated on agricultural peatlands if field-scale water-management practices are to be effective in reducing peat soil losses.

9.2. Contribution to knowledge

Greater understanding of the effect of water-table management on microbial community structure and mineralisation rates may facilitate a timelier water-table management strategy and improve agricultural peatland sustainability.

9.3. Aim

To determine the effect of water-table position on microbially mediated below ground respiration and identify those microbial groups involved in such metabolic activity.

9.4. Objectives

- Investigate the effects of such different water-table regimes on below surface respiration
- Analyse differences in microbial community structure under these different water-table regimes.

9.5. Methods

9.5.1. Field scale pilot study of below surface respiration on sites with differently spaced sub-irrigation systems.

The disturbance of any soil profile when collecting air samples from just above the ground can cause significant variation in the release of CO_2 from that soil due to the high concentrations of CO_2 trapped in soil pores. Measuring changes in atmospheric CO_2, as an indicator of microbial mineralisation of SOC, can also be confounded because above and below ground photosynthetic and respiratory activity of vegetation can add to or remove CO_2 from the atmosphere. One method used to reduce the influence of such surface vegetation on below ground respiration is the removal of surface vegetation prior to measuring temporal changes in atmospheric CO_2. However, the removal of such vegetation can also affect below ground respiratory activity; changing the availability of rhizosphere exudates to soil microbes. The length of time between clipping surface vegetation and monitoring changes in atmospheric CO_2 due to below ground respiration remains a contentious subject and has been considered in a number of studies (Osman 1971, Frossard 1976). Based on such work clipping of surface vegetation in this study was undertaken 12 hours prior to monitoring below surface respiration.

- The impact of the soil water-management regime on below surface respiration was investigated during the summer of 2003 at the West Sedgemoor research site.
- Below surface respiration was monitored on fields with sub-irrigation systems installed at 10, 25 and 40 m spacings. Monitoring points were set up at the mid-point between adjacent sub-irrigation pipes. These points were selected to quantify below surface respiration where the lowest water-table depth would be encountered under each sub-irrigation system.
- Surface vegetation around each monitoring point was clipped 12 hours prior to determining below surface respiratory activity.
- After clipping surface vegetation triplicate opaque closed chambers of known diameter and volume were installed on each monitoring point under each water-management regime (Figure 52).

Figure 52: Closed chamber systems for monitoring CO_2 evolution from below ground.

- Triplicate samples of the air were extracted from each closed chamber headspace at 30 minute intervals over a 3 hour period by inserting a needle through a rubber septum in the top of the closed chamber and drawing off a 5 ml air sample into a gas tight syringe fitted with a 3-way valve.
- All air samples were analysed for their CO_2 concentration within 24 hours of collection using a CE Instruments 8000 series gas chromatograph and hot wire detector attached to an HLPC Technology Prime chromatography data station.
- The change in the head space CO_2 concentration over a given time enabled the hourly rate of below surface respiratory activity to be calculated.

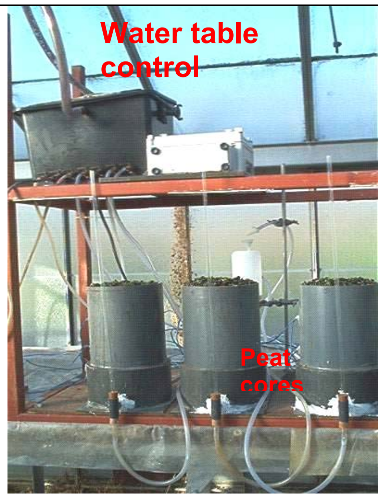
Whilst field-scale monitoring provides a real indication of the below surface respiration, changing environmental conditions can lead to high degrees of variation in results (Inubushi *et al.* 2003). The controlled management of the water level in large, intact soil cores removes the uncertainty of temporal changes in water-management regimes experienced under field conditions.

9.5.2. Monitoring below surface respiration on soil cores with controlled water-table levels.

Large soil cores were collected from the research sites at West Sedgemoor and Methwold Fen to facilitate monitoring of below surface respiration under controlled water regimes. Each water regime imposed on these soil cores aimed to simulate the range of water tables expected from ditchwater management in the field. By ensuring a constant soil water table the effects of water management on below surface respiration could be investigated.

- Nine intact soil cores of 0.3 m length and 0.20 m diameter were excavated (Figure 53 a) from each research site (Total of eighteen soil cores).
- All soil cores were maintained in a similar canopied environment to evaluate the effect of water-table position on below surface respiration (whilst also maintaining seasonal temperature changes) and remove the effect of changing soil moisture due to precipitation.
- Of each set of nine soil cores, batches of three were exposed to one of three water-table levels (water level at soil surface, 0.3 m and 0.5 m below soil surface level). The water level was kept constant in each soil core by placing the soil core on a sand-table with a regulated pressure head. The pressure head to the sand-table was kept constant using a simple feeder pipe attached to a water chamber that could be used to adjust the water-table level. Each chamber was fitted with an overflow valve and all chambers had a constant supply of water from a header tank. (Figure 53 b).

a. soil core collection from West Sedgemoor.



b. controlled water-table levels.

Figure 53: Soil cores for lysimeter monitoring of microbial respiration.

- Soil cores were acclimated to the new environmental conditions for a period of 6 months before the monitoring programme started.
- The monthly monitoring of CO2 evolution continued at monthly intervals over a period of 12 months.
- On commencing the study the surface vegetation was clipped 12 hours prior to sampling the soil CO_2 efflux.
- 12 hours after removal of surface vegetation a closed chamber was placed onto each soil core. To avoid disturbance of the soil profile (and release of soil CO_2) the closed chamber was sufficiently large enough to sit on the rim of the lysimeter. The closed chamber was sealed into place using rubber banding.
- Air samples were extracted from each closed-chamber system after zero and 24 hours by drawing off each air sample with a needle and syringe through a rubber septum situated in the top of the closed chamber.
- All air samples were analysed for their CO_2 concentration within 12 hours of sampling using a CE Instruments 8000 series gas chromatograph and hot wire detector attached to an HLPC Technology Prime chromatography data station.

9.5.3. Determination of variations in microbial community structure

Batches of five replicate peat samples were collected from Methwold Fen and West Sedgemoor from each field with different sub-irrigation spacing. Each batch of five samples was taken from one of the three soil horizons in the upper metre of peat. Each batch (peat type) was representative of one of the three stages of degradation according to the modified von Post scale (Humified, Semi-fibrous and fibrous peat). The following method was used to extract and identify phospholipid fatty acids (PLFA) from all peat samples. Subsequently PLFAs were statistically analysed using principal component analysis (PCA).

9.5.3.1. Extraction of phospholipids

The most commonly used method for phospholipid extraction is a modification of the method described by Frostegård *et al*. (1991), which uses the Bligh and Dyer (1952) extraction solvent. For this method only ester linked PLFAs are released from the soils whilst non-ester linked PLFAs remain undetected (Zelles, 1992).

The Bligh and Dyer (1952) extraction solvent consists of Chloroform, Methanol and citrate buffer solution (0.15 M Citric Acid Dihydrate and 0.15 M Tri-Sodium Citrate prepared in deionised water and adjusted to pH4) at a ratio of 1:2:0.8 (v/v/v) respectively. Butylated Hydroxyl-Toluene (0.0005 % w/v) is added to the extraction solvent as an anti-oxidant.

- Approximately 10 g of soil was weighed into sterile glass media bottles and the weight recorded. The moisture content of each batch of peat samples was determined, so that the correct Bligh and Dyer (1952) proportions of Chloroform and Methanol could be added prior to the citrate buffer solution (1:2:0.8 v/v/v). To achieve this ratio, the sum of the citrate buffer solution and soil moisture content of the sample was calculated prior to the addition of the Methanol/Chloroform mix. After these additions, a piece of PTFE tape was placed over the media bottle before capping to prevent the extraction of plasticides from the cap.
- The samples were then placed in an ultrasonic water bath at ambient temperature and sonicated[24] for 30 minutes. After shaking on a horizontal shaker for a further 30 minutes samples were left in a dark environment at room temperature for

[24] Shaken on a vibration tray.

approximately 18 hours to allow the full extraction of lipids and settlement of the samples. The samples were then centrifuged at 1500 rpm for 10 minutes.

- The upper (organic) layer of fluid was decanted off, using a Pasteur pipette, into a second sterile glass media bottle. The remaining soil pellet was washed with a further 4 ml of Bligh and Dyer solvent, and the washings added to the second bottle. Addition of approximately 250 mg Sodium Chloride at this point reduces emulsion formation. The organic layer was then separated into two phases by adding 4 ml of Chloroform and 4 ml citrate buffer. This was left overnight at 4 °C to facilitate separation of the two layers. After separation the samples were centrifuged for 10 minutes at 1500 rpm. The upper layer was removed by Pasteur pipette and discarded.
- The remaining organic layer was evaporated to dryness in a water bath at 37 ºC under a stream of Nitrogen to prevent breakdown of the unsaturated fatty acids. The samples were then stored at -20 ºC until fractionated.

9.5.3.2. Fractionation of lipid extracts

- Lipid fractionation was achieved using commercially available solid phase silica extraction cartridges (3 ml/500 mg silica Sep-pak VacTM) with a manifold attached to a vacuum pump.
- Cartridges were pre-washed with 2 ml each of Methanol, Acetone and then Chloroform. Residual solvent was dried from the sorbent bed in the cartridge by leaving cartridges attached to the manifold and drawing air through the cartridge for 5 minutes. Following washing and drying, the cartridges were conditioned with 2 ml of Chloroform. After conditioning, it becomes essential that the sorbent material does not dry out during separation. The rate of elution from the cartridges was therefore adjusted to approximately 2 ml min^{-1}.
- The lipid extract was reconstituted in 500 µl of Chloroform. Samples were then evaporated to dryness in a water bath at 37 ºC under a stream of Nitrogen. The re-constituted sample was then added to the cartridge by filtering through a Pasteur pipette packed with sodium sulfate (to eliminate contamination by the aqueous phase).

- The lipid classes were selectively eluted from the cartridge by increasing the polarity of the elution solvent. The extract was fractioned by eluting neutral lipids with 5 ml Chloroform; glycolipids with 12 ml Acetone; and polar lipids with 8 ml of Methanol. The polar lipid fraction was collected in sterile media bottles, and then evaporated to dryness at 37 ºC under a stream of Nitrogen. As light degrades phospholipids excessive exposure to light was avoided.
- The dry fractions were stored at -20 ºC.

9.5.3.3. Mild alkaline methanolysis

- The phospholipid fraction was methylated by mild alkaline methanolysis (Dowling *et al*., 1986).
- During this stage there must be no water present, as this will attack the double bonds and compete with Methanol for the fatty acids which can yield free fatty acids rather than methyl esters. This is achieved by drying the solvents used over anhydrous sodium sulfate.
- The polar lipid fraction was reconstituted using 1 ml of Toluene: Methanol (1:1; v/ v). Following reconstitution, 1 ml of Methanolic Potassium Hydroxide (0.2M Potassium Hydroxide prepared in Methanol) was added and the solution incubated at 37 ºC for 30 minutes.
- To stop acoholysis and neutralise the samples to pH 6-7 0.3 ml of 1 Molar Acetic Acid was added. Extraction of the derived fatty acids was achieved by adding 5 ml of Hexane, Chloroform (4:1 v/v) and 3 ml of deionised water to the sample. At this stage Sodium Chloride (100-200 mg) was also added to break up any emulsion.
- The sample was sonicated for 30 minutes to disperse the lipids and then centrifuged to separate the two layers.
- The aqueous (lower) layer was removed by Pasteur pipette and discarded.

9.5.3.4. Base wash

- To clean the sample and remove any underived fatty acids 3 ml of Sodium Hydroxide (12 g l^{-1}) was added as a base wash reagent. The high pH created by the base ionises any free acids and therefore makes them more polar and less soluble in the organic phase. The sample was then centrifuged at approximately 1500 rpm to separate the two phases. The upper organic phase was removed to a sterile glass media bottle via Sodium Sulfate filters.
- A further 3 ml of Hexane: Chloroform (4:1 v/v) was added to the aqueous layer to wash any residues. This was then filtered through a sodium sulfate filter to combine it with the initial solvent. The filter was then washed with another 1 ml of Hexane: Chloroform (4:1 v/v). The solvent was then evaporated to dryness at 20-25 ºC under nitrogen and stored under nitrogen at -20 ºC until identification.
- The dried sample was reconstituted with 0.1 ml of hexane prior to Gas Chromatogram (GC) injection.

9.5.3.5. Gas chromatography

- A GC system was used for fatty acid analysis.
- The volume of sample injected into the GC was 1.0 µl. The resulting ester linked fatty acid methyl esters were separated by capillary GC and identified by their retention times.
- The gas chromatography (GC) column was fitted with a 60 m SE-54 (95 % dimethyl-, 5 % phenylmethyl-polysilicoxane stationary phase). This consisted of two columns, a 30m x 320 µm (internal diameter) SE 54 connected to 30m x 250 µm (internal diameter) SE 54, both columns with 0.25 µm δf (δf = film thickness) (Alltech). Helium was used as the carrier gas (1 ml min^{-1}).
- Fatty acid methyl esters (FAMEs) were separated by using a temperature program; starting at 60 °C for 1 minute, increasing at 25 °C per minute to 145 °C , followed by 25 °C per minute to 250 °C and 10 °C per minute until reaching 310 °C. Fatty Acid Methyl Esters (FAMEs) were detected using a Flame Ionization Detector (FID) operating at 320 °C.

- The separated fatty acid methyl esters were identified by comparison of GC retention time against a standard qualitative bacterial acid methyl ester mix (Supelco). The Supelco standard contains 26 fatty acid methyl esters of bacterial origin.

9.5.3.6. Fatty acids designation

A:BωC, where A is the total number of carbon atoms, B is the number of double bonds and C indicates the position of the double bond from the aliphatic methyl end (ω) or the carboxyl group end (Δ) of the molecule. The geometry of this bond is indicated by *c* (for *cis*) or *t* (for *trans*). The prefixes *i* and *a* refer to *iso*- and *anteiso*-methyl branching, respectively. Mid-chain methyl branches are designated by *Me* preceded by the position of the methyl group from the acid end of the molecule. Cyclo-propyl fatty acids are designated *cyc*. Fatty acids in the standard are listed in Table 10.

Elution Order	Fatty acid methyl ester	Elution Order	Fatty acid methyl ester
1	Me tetradecanoate (14:0)	18	Me *cis*-(, 10-methylenehexadecanoate (cyc 17
2	Me 13-methyltetradecanoate (*iso*-15:0)	19	i17:1
3	Me 12-methyltetradecanoate (*anteiso*-15:0)	20	Me heptadecanoate (17:0)
4	Me pentadecanoate (15:0)	21	17:0 isomer
5	Me 14-methyl pentadecanoate (*iso*-16:0)	22	Me 2-hydroxyhexadecanoate (2OH-16:0)
6	Me 14-methyl pentadecanoate (anteis*o*-16:(	23	i18:0
7	Me-cis-9-hexadecanoate (16:1ω9)	24	Me *cis*-9, 12-octadecadienoate (18:2ω6,*cis*)
8	Me *cis*-9-hexadecenoate (16:1ω7*cis*)	25	Me *cis*-9-octadecanoate (18:1ω9*cis*)
9	Me *cis*-9-hexadecenoate (16:1ω7*trans*)	26	Me *trans*-9-octadecenoate (18:1ω9*trans*) and Me *cis*-11-octadecanoate (18:1ω7*cis*)
10	16:1w5	27	Me *cis*-11-octadecanoate (18:1ω7*trans*)
11	Me hexadecanoate (16:0)	28	i18:1
12	Me17:0isomer (?)	29	Me octadecenoate (18:0)
13	Me 17:0 isomer (?)	30	19:2
14	Me 17:0 isomer (?)	31	Me *cis*-9, 10-methyleneoctadecanoate (cyc-19
15	Me. 15-methylhexadecanoate (i17:0)	32	Me nonadecanoate (19:0)
16	ai17:0	33	Me eicosanoate (20:0)
17	17:1		

Table 10: Reference fatty acids and Methyl Esters on an SE54 column.

Microbial identification group	Fatty acid group	Fatty acid
Total bacterial abundance	Various fatty acids	*i*15:0, *ai*15:0, 15:0, *i*16:0, 16:1ω9, 16:1ω7t, *i*17:0, *ai*17:0, 17:0, *cyc*-17:0, 18:1ω7, *cyc*-19:0
Stress indicator		Ratio of *Trans* to *cis* 16:1ω7
Gram-negative bacteria and some anaerobic Gram-positive bacteria	Cyclopropane	*cyc*-17:0, *cyc*-19:0
Gram-negative	Mono-unsaturated	16:1ω9c, 16:1ω7c, 16:1ω7t, 16:1ω5c, 18:1ω9c, 18:1ω7c 18:1ω7t
Gram-positive and some sulfate-reducing Gram-negative bacteria	Terminally branched, saturated	*i*15:0, *ai*15:0, i16:0, *i*17:0
Sulfate-reducing bacteria	Methyl branched and branched unsaturated	10Me16:0, *i*17:1ω7, *i*15:0
Type-I methanotrophs	Mono-unsaturated	16:0, 16:1ω8
Type-II methanotrophs	Mono-unsaturated	18:1ω8
Eucaryotes (particularly fungi)	Polyunsaturated, straight chain	18:2ω6
Arbuscular mycorrhizal fungi	Monounsaturated	16:1ω5
Actinomycetes	Methyl branching on 10th carbon atom	10:Me16:0, 10Me17:0, 10Me18:0

Table 11: Phospholipid fatty acids corresponding to microbial groups.

9.5.3.7. Fatty acids analysis

Haack *et al.* (1994) state that Principal Component Analysis (PCA) is the most useful method for statistically analysing the large number of variables resulting from a PLFA analysis. PCA reduces the very large numbers of fatty acid gas chromatography peaks to a smaller set of uncorrelated variables whilst still retaining most of the original variables information. PCs are ranked such that the first PC contains most of the original variation between PLFAs and the second and subsequent PCs contain respectively lower amounts of the total variation. To make the analysis of the PCA readily interpretable, peak values obtained by gas chromatography are normalised by dividing the amount of each PLFA by the total amount of PLFA in that particular sample; to indicate the relative proportion of each PLFA in the sample. PCA can therefore indicate where shifts in PLFA profiles occurs which can then be ascribed to variations in microbial communities as a response to environmental conditions (Frostegård *et al.*, 1996). By using PCA the relationships between individual PLFAs or batches of PLFAs in soil samples can be evaluated utilising two-dimensional plots of the PCs. Samples with similar PLFA values tend to have a common pattern of PLFA composition and are therefore closer together in the PCA plots. Subsequently, variance between PC coordinates can be statistically assessed for variance to determine whether water-management regime leads to differences in microbial community structure. Borga *et al.* (1994) and Sundh *et al.* (1997) demonstrate the importance of combining the phospholipid fatty acid method with PCA in peat soil investigations.

9.6. Results

9.6.1. Field scale pilot study of below surface respiration on sites with differently spaced sub-irrigation systems.

Field monitoring of the effects of sub-irrigation on below ground respiration at West Sedgemoor are given in Figure 54. The below surface respiration rate ranged from 0.8 – 17.7 mg CO_2-C m^{-2} hr^{-1} (Table 80, Appendix F.1) and, during the short period of summer-time monitoring, suggested that CO_2-C efflux was greater on fields with closer spaced sub-irrigation systems (wetter soils). The findings compare with the lower end of those values reported by Nieven *et al.* (2005), whose values ranged from 17.3 – 346 mg CO_2-C m^{-2} hr^{-1} (reported as 0.4–8.0 µmol CO_2 m^2 s^{-1}). However, CO_2-C data reported by De Busk and Reddy (2003) shows the range of CO_2-C efflux can be even greater still; ranging from 6.8 – 65.3 g CO_2-C m^{-2} h^{-1} (reported as 0.68 to 6.53 mg C cm^{-2} h^{-1}) when water-tables levels were maintained across the range + 0.10 to -0.15 m (relative to mean field level).

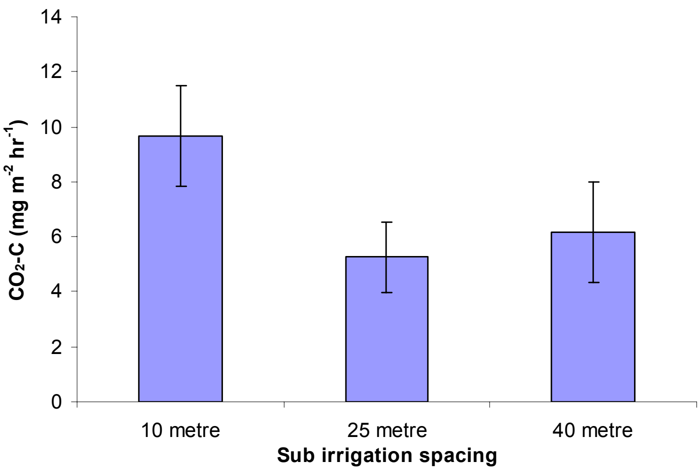


Figure 54: Field observations of CO_2-C efflux under different sub-irrigation systems at West Sedgemoor during early summer 2003 (error bars denote standard error of the mean).

In this pilot study the degree of variability in the field-scale below-ground respiration rate was large (Table 80, appendix F.1) and the trend was not statistically significance ($p=0.13$). However, the trend does suggest that as the water table is dropped in the ditches during the early spring months (chapter 2.4.2.2) those fields with closely spaced sub-irrigation do experience aeration, but do not dry to the same extent as fields where the sub-irrigation system spacing is greater. On fields with closely spaced sub-irrigation the conditions in the upper soil horizons appear more favourable (moist) for below ground respiration during the summer. The findings appear contrary to those of van Huissteden *et al.* (in press).

The considerable variability in observed CO_2-C efflux reported above may result from inherent soil variability at such scales (Nay and Bormann, 2000) and the difficulties of field-scale water-table management.

The pilot study was undertaken during the particularly dry summer of 2003 and there were issues concerning water-table management at the time. To discount the effects of such changeable water-table management it was decided to investigate the seasonal effect of water level management on CO_2-C efflux in a more controlled environment.

9.6.2. Monitoring below surface respiration on undisturbed soil cores with controlled water-table levels.

The below ground respiration findings are presented from soil cores collected from West Sedgemoor and Methwold Fen. These soil cores were minimally disturbed to best simulate field conditions. This meant surface vegetation, if present, was maintained and clipped prior to monitoring of CO_2 efflux from the soil surface.

CO_2-C efflux ranged from 0.02 to 1.8 g m^{-2} d^{-1} (Table 81, Appendix F.1) on soil cores from West Sedgemoor (Figure 55) and from 0.05 to 1.67 g m^{-2} d^{-1} (Table 83, Appendix F.1) on soil cores from Methwold Fen (Figure 56). The results compare with the lower to middle end of values reported by Moore and Dalva (1997) from

0.8 m long intact soil cores; which ranged from 0.456 to 2.88 g CO_2-C m^2 d^{-1} under saturated conditions to between 2.16 and 3.79 g CO_2-C m^2 d^{-1} with a water table at 0.4 m below the surface.

Analysis of variance of the CO_2-C efflux from soil cores from West Sedgemoor (Table 81, Appendix F.1) indicates there is a significant increase in below ground respiration from winter to summer ($p<0.001$) and also an increase when the water level is dropped from the surface to 0.5 m below the surface ($p<0.001$).

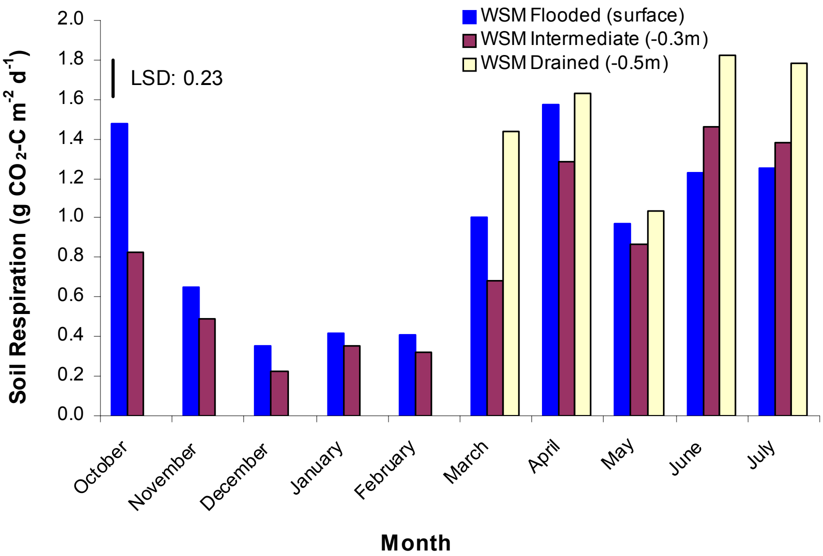


Figure 55: Below ground respiration determined from lysimeters collected from West Sedgemoor.

Surprisingly, the bare Methwold Fen soil core respiration rates (no vegetation) had similar respiration values to those of West Sedgemoor[25]. Analysis of variance of Methwold Fen soil core below surface respiration rates (Table 83, Appendix F.1) indicates that respiration was greatest during the spring and summer months ($p<0.001$). There was a much clearer effect of water-table depth on below ground respiration on Methwold Fen soil cores (Figure 56) than on West Sedgemoor soil cores; demonstrating that increased drainage significantly increased below ground respiration ($p<0.001$).

[25] Methwold Fen soil cores did not have surface vegetation that contributed an additional and alternative source of CO2 to the atmosphere.

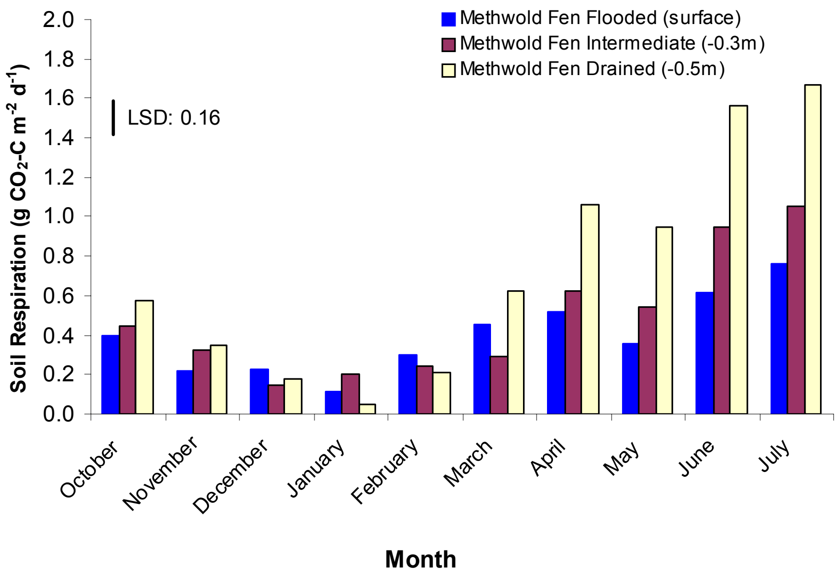


Figure 56: Below ground respiration determined from lysimeters collected from Methwold Fen.

9.6.3. Variations in microbial community structure under differing sub-irrigation spacings.

In this work specific groups of microbes are discussed that highlight the difference in microbial community structure under different soil water regimes and land-uses. Differences in the structure of microbial communities are liable to determine the type of respiratory pathway employed under a particular water-management regime and hence dictate the rate of organic carbon mineralisation.

In all twenty-five identifiable phospholipid fatty acids (PLFAs) were detected in the peat samples from West Sedgemoor and Methwold Fen. The relative abundance of these PLFAs is reported in Table 85 and Table 86 (Appendix F.2) for West Sedgemoor and Methwold Fen, respectively. These PLFAs were ascribed to particular microbial groups according to the findings of Zelles (1992), as presented in Table 11 (section 9.5.3).

In West Sedgemoor peats the proportion of bacterial microbes in the different peats under the different water-management regimes are shown in Table 12.

Source	Soil type	Irrigation spacing (m)	Total bacterial abundance	% G- and G+ anaerobic (Cyc17:0 and 19:0)	G+ (i15:0, ai15:0, i16:0 and i17:0)	Fungal: Bacterial ratio
WSM	Peaty Loam	10	58.30 (1.55)	25.21 (1.07)	27.03 (0.63)	-
WSM	Peaty Loam	25	52.66 (0.38)	20.98 (1.23)	26.56 (0.96)	-
WSM	Peaty Loam	40	53.06 (0.36)	19.33 (0.99)	25.75 (1.02)	1:29
WSM	Humified	10	56.26 (1.36)	30.56 (1.48)	20.80 (0.78)	-
WSM	Humified	25	55.77 (5.71)	24.80 (4.77)	25.99 (0.82)	-
WSM	Humified	40	53.85 (0.19)	21.44 (0.14)	20.39 (0.25)	1:70
WSM	Semi Fibrous	10	46.29 (0.75)	21.96 (0.82)	18.79 (0.10)	-
WSM	Semi Fibrous	25	44.91 (1.52)	19.16 (1.67)	17.21 (3.20)	-
WSM	Semi Fibrous	40	53.51 (0.66)	25.52 (0.75)	11.76 (0.73)	1:34

Table 12: Relative abundance of different microbial groups in West Sedgemoor (WSM) peats (standard error of the mean in parentheses).

Analysis of variance (Table 87 to Table 89 appendix F.2) indicates that total bacterial abundance is considerably reduced in deeper horizons which are continually saturated ($p<0.001$). There are significantly more gram-negative bacteria and gram-positive anaerobic bacteria in surface horizons that have closer spaced sub-irrigation ($p=0.03$). There are also significantly more gram-negative and gram-positive anaerobic bacteria in the continually saturated, deeper, wetter peats ($p=0.05$). There is a significant increase in the presence of gram-positive bacteria in drier surface horizons than in deeper, wetter peats ($p<0.001$) and a significant decrease in gram-positive bacteria in surface peats that are wetter[26] ($P<0.001$).

The proportion of bacterial microbes in the different peat horizons and fields from Methwold Fen are shown in Table 13.

Source	Soil type	Irrigation spacing (m)	Bacterial abundance	% G- and G+ anaerobic (Cyc17:0 and 19:0)	G+ (i15:0, ai15:0, i16:0 and i17:0)	Fungal: Bacterial ratio
Methwold Fen	Amorphous	20	55.96 (1.09)	27.31 (0.62)	23.03 (0.79)	1:4
Methwold Fen	Amorphous	20	52.36 (1.66)	21.79 (2.02)	24.72 (1.62)	1:33
Methwold Fen	Amorphous	20	51.70 (2.21)	22.55 (0.75)	18.29 (0.84)	-
Methwold Fen	Semi Fibrous	20	47.12 (3.01)	20.40 (3.62)	20.42 (1.23)	-
Methwold Fen	Semi Fibrous	20	55.36 (0.52)	19.46 (0.43)	20.94 (0.28)	1:21
Methwold Fen	Semi Fibrous	20	52.26 (1.19)	21.62 (1.04)	18.83 (0.45)	-
Methwold Fen	Fibrous	20	50.56 (1.29)	23.90 (2.80)	21.25 (1.89)	1:60
Methwold Fen	Fibrous	20	54.44 (0.13)	18.84 (0.83)	21.70 (0.51)	1:67
Methwold Fen	Fibrous	20	54.98 (0.78)	23.85 (2.39)	21.14 (0.45)	-

Table 13: Relative abundance of different microbial groups in Methwold Fen (MF) peats (standard error of the mean in parentheses).

[26] *i.e.* under closer spaced sub-irrigation.

Analysis of variance (Table 90 to Table 92, appendix F.2) indicates there are no significant differences in total bacterial abundance between different peat horizons ($p=0.47$) or between different fields ($p=0.31$). Gram-negative and gram-positive anaerobic bacteria do not differ significantly between soil horizons ($p=0.17$) but do differ significantly between locations ($p=0.03$). There are no significant differences in the abundance of gram-positive bacteria between peat horizons ($p=0.08$) but there is a significant change between locations ($p<0.001$).

At West Sedgemoor no fungal PLFAs were identified in the saturated peat samples but in the drier peats fungal PLFA was present. The Bacterial to Fungal ratio in these peats was higher in the deeper horizons. At Methwold Fen the soil Fungi were evident in all horizons and the Bacterial to Fungal ratio again appeared highest in the drier surface horizons. This is in agreement with Zeller *et al*. (2001) finding; that natural microbial communities are often characterised by high Bacterial to Fungal ratios compared to low ratios in managed systems.

Principal Component analysis (PCA) of all PLFAs is depicted in Figure 57; 'a' to 'c' for West Sedgemoor peats; and, 'd' to 'f' for Methwold Fen peats. These plots are indicative of variations in total microbial community structure between soil horizons and between fields under either variable water management or affected by other environmental conditions.

On West Sedgemoor peat samples the first three Principal Components (PC) account for 78 per cent of the variation in phospholipid fatty acid composition of soil microbes from different horizons and from fields under different water-management regimes. PCs 1 and 3 account for 57 per cent of the variation between phospholipid fatty acids resulting from differences between soil horizons only. PC 2 accounts for 21 per cent of the variation due to the combined effects of soil horizon and water-management strategy.

On Methwold Fen peat samples the three PCs of interest account for 70 per cent of the variation in phospholipid fatty acid composition of soil microbes from different horizons and between fields of similar water management but differing soil pH. PC 1 accounts for 44 per cent of the variation, PC2 for 19 per cent and PC5 for 7 per cent.

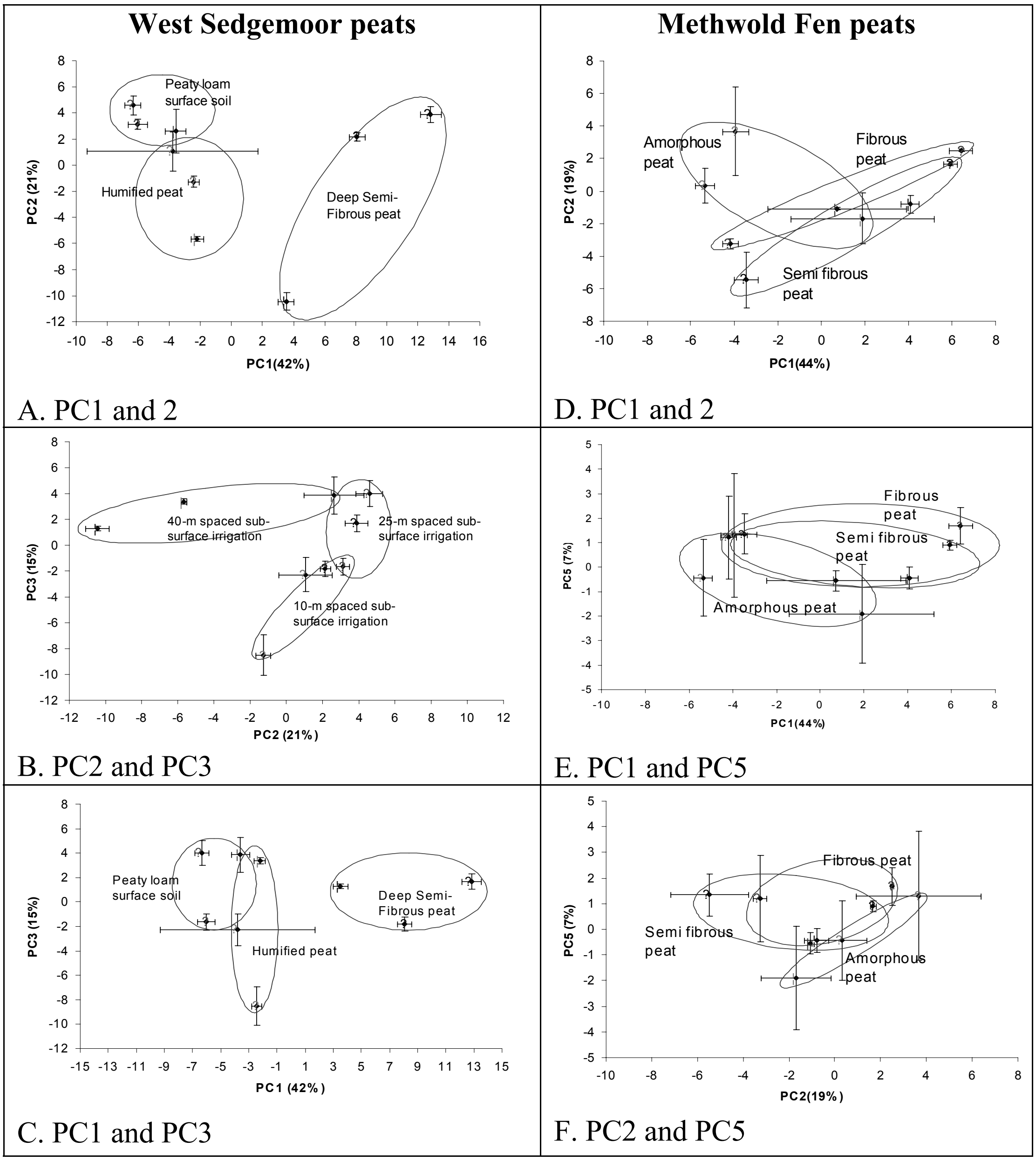


Figure 57: PCA of PLFAs from West Sedgemoor (a: peaty loam, b: humified peat and, c: semi-fibrous peat horizons) and Methwold Fen (d: amorphous peats, e: semi-fibrous peats and, f: fibrous).

At West Sedgemoor analysis of variance of PCs indicates there are significant differences in the total microbial community structure between soil horizons (PC1 $p<0.001$, PC2 $p<0.001$ and PC3 $p<0.001$) and between sub-irrigation spacings (PC2 $p<0.001$ and PC3 $p<0.001$). In West Sedgemoor peat samples plot 'a' indicates the microbial communities are more similar in the upper 2 peat horizons. Plot 'b' suggests differences in microbial communities between wetter soil horizons locations than drier horizons and locations and plot ‘c’ that wetter soil horizons and wetter locations differ from drier horizons and locations.

At Methwold Fen analysis of variance of PCs indicates there are no significant differences in total microbial community structure between soil horizons (PC1 $p=0.30$, PC2 $p=0.29$ and PC5 $p=0.26$) and Figure 57 plots ‘d-f’ all demonstrate this overlap in microbial community composition. Where differences in the microbial community do occur in Methwold Fen peat samples it is believed to result from differences in soil pH (which ranges from 4.4-6.6 in the upper 0.5 m of soil profile to between 3.6-7.1 in the lower 0.5-1.0 m of soil profile) rather than differences in water-management practices.

Generally the cyc17:0 and cyc19:0 fatty acids are in greater abundance in wetter horizons / locations and account for the greater proportion of variation reported in West Sedgemoor peat samples. Lechevalier and Lechevalier (1988) suggest that such cyclo-propane fatty acids are generally found in larger quantities in a number of G-negative genera and only a few G-positive bacteria, whilst methyl-branched fatty acids (such as i15:0, ai15:0, i16:0 and i17:0) are more common in G-positive microbes. At West Sedgemoor there appear to be a greater abundance of such gram-negative and anaerobic gram-positive bacteria in the wetter environments, which agrees with Hatori (1988) and Petersen *et al.* (1997) finding that gram-negative bacteria are more prevalent in wetter environments.

9.7. Discussion

The previously reported potential for seasonal soil moisture deficit without any form of water-table management (chapter 8.6.1) is liable to cause a drop in the water table and an associated increase in the depth of vadose zone. This would lead to greater pressure potentials being experienced in the vadose zone and a greater likelihood of biochemical mineralisation of deeper peat horizons. Chapter 8.6.2 demonstrates that ditchwater management, in conjunction with sub-irrigation, raises the water table and reduces the thickness of vadose zone. The findings of this chapter demonstrate that such water management practices affect the capacity of different microbial groups to function.

9.7.1. Microbial mineralisation of SOM

In the field-scale pilot study of the effects of sub-irrigation on below ground respiration there appeared to be a trend of increased respiration from more closely spaced sub-irrigation systems. van Huissteden *et al.* (in press) found that an increase in CO_2 evolution also resulted from a lowered water-table but also reported that the rate of such soil respiration declined over a period of months after the initial change in water-table level. van Huissteden *et al.* (in press) suggests that this reflects a slow depletion of readily available labile compounds for microbial respiration. At West Sedgemoor it is believed that the wetland grass species present on these peats are better adapted to the wetter environment found there. Where closer spaced sub-irrigation is employed these grasses may contribute more root exudates to the rhizosphere's labile carbon pool than under drier conditions. During the spring and summer months this readily available source of carbon energy is liable to facilitate greater microbial respiration in the root zone. Though there is increased metabolic activity the availability of easily metabolised root exudates may reduce the mineralisation of SOC.

The study of below surface respiration from West Sedgemoor soil cores corroborate the rather variable trend in the field-scale pilot study (*i.e.* where the water-table level is 0.5 m below the surface respiration optimal soil moisture conditions are created in the surface soil horizons for soil respiratory activity). This situation translates to the field-scale summertime management strategy where a ditchwater level at 0.3 m below mean field level on those fields with 10 m spaced sub-irrigation, as the field-scale water table is slightly lower that that of -0.3 m employed in the ditch system (Section 2.4.2.2). The study of West Sedgemoor soil core respiration data also demonstrates that where the field water level is closer to the surface than -0.5 m then respiration becomes limited by the almost saturated environment during summer months. The trend in field data also suggests, however, that where the water table is equal to or deeper than 0.5 m below the soil surface (25-40 m spaced sub-irrigation systems) then respiration again becomes limited; as the soil in the middle of the field probably experiences pressure potentials in the surface horizons at least equal to if not much greater than -0.5 m (considered in Chapter 8.6).

An additional observation on the rate of below surface respiration of grass covered soil cores from West Sedgemoor is that below surface respiration continued on the wetter soil cores (saturated and -0.3 m pressure potential) during the autumn and winter months whilst the soil cores experiencing -0.5 m pressure potential did not. During the winter period the grasses died back on the soil cores experiencing -0.5 m pressure potential but remained on the wetter soil cores. It is believed that the grasses on wetter peat soils are better adapted to such an environment and continue to produce root exudates during the winter months. In the greenhouse environment used to maintain the soil cores the air temperature was slightly elevated during winter months and this may have aided such continued growth of surface vegetation and hence facilitated the continued respiration in the rhizosphere. Indeed, Billings *et al.* (1977) estimates that such root participation in soil respiration can account for between 30 - 70 per cent of total respiration, depending on habitat. The concept of easily available organic carbon enhancing respiration was explored in chapter 7.5.3 on substrate induced respiration.

Though there are reservations about using the measured below surface to quantify the soil organic matter mineralisation, the monthly CO_2 efflux data has been used to estimate theoretical annual soil organic matter mineralisation and subsidence rates (assuming no alternative energy source is available). The annual soil organic matter mineralisation is based on the assumption that organic carbon constitutes 58 per cent organic matter and that the weighted mean SOM content of the 0.3 m length of West Sedgemoor peat core was 53 per cent (based on peat horizon thickness and SOM percentage determined in chapters 5 & 6). The estimate of annual subsidence assumes an averaged dry bulk density of 0.23 g cm^{-3} for the 0.3 m peat profile (based on chapter 5 & 6 data). The annual estimates for both data sets are summarised in the table below, according to the monthly values shown in Table 82 (Appendix F.1).

	Treatment		
	Flooded	Intermediate	Drained
OM loss (t ha^{-1} yr^{-1})	3.3	2.9	2.9
Subsidence cm yr^{-1})	0.14	0.12	0.12

Table 14: Estimated annual loss of organic matter and subsidence of West Sedgemoor due to microbial respiration (CO_2) of peat.

The results suggest there is very small difference in organic matter mineralisation and annual rates of subsidence between peat soil systems with different water management strategies. Indeed, there is marginally greater subsidence where soils are flooded. The findings do not agree with the observed long-term change in surface elevation reported in chapter 5. The lack of agreement suggests the assumption that a considerable proportion of soil CO_2 efflux is due to the mineralisation of root exudates is correct (*i.e.* the greater respiration from soil cores that have a water table close to the surface may be due to the continued growth of grass and release of root exudates in these soil cores during the winter months). If one assumes, though, that such CO_2 efflux is solely due to the mineralisation of soil organic matter mineralisation then during the winter months those peat cores with a higher water level appear to continue losing organic matter. This latter supposition agrees with findings in chapter 7.5.1; that a cooler and wetter environment can provide optimal conditions for respiratory activity of some West Sedgemoor peats. The mineralisation of organic carbon from West Sedgemoor peats and the role of root exudates are considered further in chapter 10.2.1.

The rate of respiration from Methwold Fen soil cores is believed to provide a more definitive measure of the rate of microbial mineralisation of SOM; as Methwold Fen soil cores had no surface vegetation that could provide additional sources of organic carbon for microbial metabolic processes. The estimation of monthly soil organic matter mineralisation is depicted in Figure 58 (Table 84, Appendix F.1). The estimate is based on the assumption that all the organic carbon in respired CO_2 comes from SOM mineralisation and that organic matter is 1.724 times (58 %) greater in mass than SOC (Bellamy *et al.,* 2005). Also, that the 0.3 m long Methwold Fen soil cores only contain amorphous peat with a SOM content of 66 per cent.

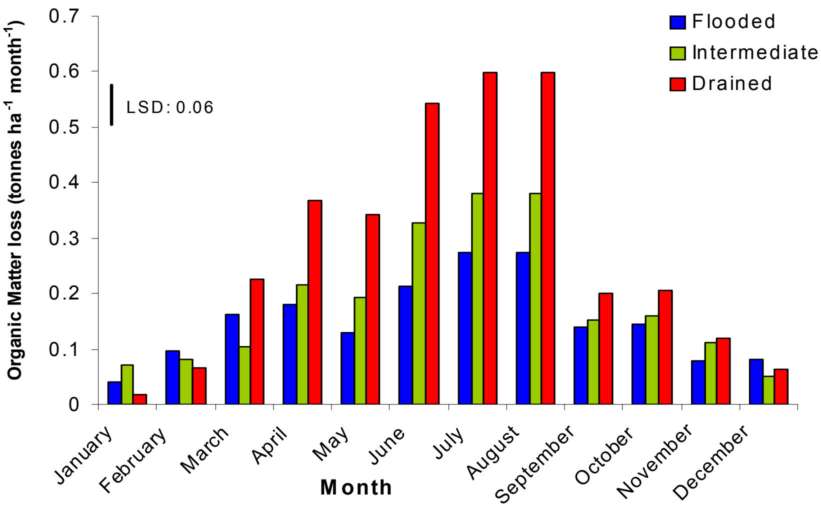


Figure 58: Estimation of monthly loss of organic matter at Methwold Fen due to microbial mineralisation.

Totalling the monthly average of organic matter loss due to microbial respiration under each water-management regime suggests significantly more SOM is lost each year where peats experience around -0.5 m pressure potential than peats that are saturated (Table 84, Appendix F.1). With a knowledge of the dry bulk density of the peat in the soil core (amorphous peat: 0.35 g cm^{-3}) it was also possible to calculate a theoretical annual subsidence rate due to microbial mineralisation of Methwold Fen peats (Table 15).

	Treatment		
	Flooded	**Intermediate**	**Drained**
OM loss (t ha^{-1} yr^{-1})	1.8	2.2	3.3
Subsidence cm yr^{-1})	0.04	0.05	0.09

Table 15: Estimated annual loss of organic matter and subsidence of Methwold Fen due to microbial respiration (CO_2) of peat.

The first point of note is that both the SOM loss from and estimated subsidence of Methwold Fen soil cores is considerably less than the estimated losses from West Sedgemoor peat cores. This appears to affirm the supposition that root exudates are contributing to CO_2 efflux from West Sedgemoor peat cores.

Contrasting the above rate of SOM loss and subsidence against the surveyed long-term annual subsidence rate of Methwold Fen reported in chapter 5 (1-2 cm year^{-1}), the findings appear low but acceptable. The estimates suggest that mineralisation of these peats only accounts for between 5 and 10 per cent of the annual averaged change in surface elevation. Most importantly, the results imply that different water-management strategies can have a considerable impact on subsidence and that inundating the peat soils could halve the rate of mineralisation of SOM.

9.7.2. Microbial community structure in peat soils under different sub-irrigation systems

In West Sedgemoor peats the water management regime and depth of peat horizon lead to clear differences in the type and abundance of soil microbes. Equally, where deeper drainage has been employed at Methwold Fen there are greater differences in microbial community structure between different locations than between soil horizons.

The investigation did not identify the wide range of microbes reported by Sundh *et al.* (1997) or Borga (1994). But, the greater abundance of cyclo-propane PLFAs found in the wetter peats of West Sedgemoor is in agreement with Ratledge and Wilkinson (1988) statement; that cyclo-propane PLFAs are a strong indicator of anaerobic bacteria. The results are also in general agreement with a number of studies; that gram-negative bacteria are better adapted to wetter environments, due to their thinner cell wall and retention of digestive enzymes in the periplasm (Hatori 1988, Petersen *et al.* 1997).

Sundh *et al.* (1997) and Stout (1971) both state that peats' microbial composition varies between wet and dry environments and with depth and it therefore seems probable that the greater proportion of gram-negative and anaerobic microbes found in the wetter horizons (subject to closely spaced sub-irrigation) are less likely to mineralize the SOM as efficiently as the gram-positive microbes found in drier surface horizons of West Sedgemoor peats.

The Methwold Fen peats have a greater range and abundance of PLFAs, indicating greater microbial biodiversity and less anaerobic bacteria. The greater abundance of gram-positive bacteria throughout the soil profile suggests there are more efficient aerobic microbes throughout the soil profile. These gram-positive microbes are known to be more tolerant of moisture stress, as they can form resting spores if environmental conditions become unfavourable (Prescott *et al.*, 1996). The results are also in agreement with Stout (1971) assessment of cultivated peat soils.

The degree of variation in PLFAs is greater between different fields than between peat horizons. Such differentiation most likely results from factors other than the water-management strategy; such as the considerable variation in soil pH reported in chapter 5.5.3. This would be in general agreement with Waksman and Stevens (1929) who reported that soil bacteria are less numerous in highly acid peats.

9.8. Conclusions

Although the water-management practices adopted at West Sedgemoor can enhance water-table levels, the field-scale pilot study of below surface respiration suggests that the low pressure potentials resulting from such closely spaced sub-irrigation can lead to higher below surface respiration during the summer months (but only when ditchwater levels are lowered). As such monitoring of below surface respiration suggests increased microbial activity with closer spaced sub-irrigation consideration must be given to the ditchwater regime that is in operation and the type of land-use. On wet grasslands the rate of below ground respiration may be attributed to microbial metabolisation of root exudates rather than SOM.

On Methwold Fen undisturbed peat soil cores where the water table is held high, experiments provide tangible evidence that saturation of peat soils impedes below surface respiration. Where the water table is held at typical levels (between -0.3 and -0.5 m below ground level) the rate of mineralisation of SOC is promoted, but still only appears to account for between 5 to 10 per cent of peatland subsidence. These estimated rates of annual mineralisation are low relative to other research (Schothorst 1982, Price *et al.* 2003). Schothorst (1982) estimates that 65 per cent of long-term subsidence in the vadose zone is due to shrinkage, and that 85 per cent of this shrinkage results from microbially mediated mineralisation of SOM.

Irrespective of the lower rates of mineralisation, the results appear to agree with the general trend in predominant soil microbial communities addressed in chapter 9.7.2, as wetter peats have predominantly less efficient anaerobic microbes.

The wetter West Sedgemoor peats have a greater abundance of anaerobic bacteria in all deeper, wetter horizons and surface horizons where closely spaced sub-irrigation is employed whilst the more frequently and deeply drained peats from Methwold Fen have a greater abundance of more hardy gram-positive microbes. These latter microbes are able to survive under harsher environmental conditions and are probably more efficient at aerobic mineralisation of SOM.

Overall, water-table management does appear to affect SOM mineralisation and therefore can improve the sustainability of peat soils. Such water management can be further enhanced by sub-irrigation if ditchwater-management planning is appropriate. However, inappropriate ditchwater management can mean the sub-surface system can exacerbate the rate of SOC mineralisation.

10. Research synthesis and future water management scenarios

This work has focussed specifically on low-lying agricultural peatlands and the ability of improvements in water-management practices to reduce the mineralisation and degradation of such soils. The historical drainage of low-lying peatlands in the UK has been for intensive agricultural operations. The increased requirement for land access and the use of heavy machinery on such low-lying peatlands have therefore lead to much deeper drainage, and hence much greater rates of subsidence, than experienced on other peatlands. The potential ease with which agricultural water-management practices can be improved is much greater on these much flatter low-lying peatlands.

It is undoubtedly the case that the greatest rate of peatland subsidence occurs during initial drainage of such land (Bowler 1980). Previous research has shown that immediately after deep drainage the rate of peatland subsidence can be greater than 18 cm year^{-1} (Hutchinson 1980, Driessen and Rochimah 1976, Stephens *et al.* 1984). Equally, Price *et al.* (2003) report that removal of the acrotelm alone can result in peatland subsidence rates up to 3.7 cm year^{-1}. This work demonstrates that longer-term subsidence rates of low-lying agricultural peatlands vary considerably, according to land-use and water-management strategy. The results are in general agreement with reports by Brown *et al*. (2003); that shallow drained peatlands under grass (which are subject to low stocking and grazing density) have negligible rates of subsidence when ditchwater regimes have been held within -0.3 m of the mean field level.

At West Sedgemoor the reduced rate of subsidence is most likely also aided by the capping of the peat with an organic peaty loam horizon which has a lower porosity at saturation (71 per cent) than the peat soils (82 to 92 per cent), a relatively small dominant pore size (26 μm diameter) and a lower saturated vertical hydraulic conductivity (0.24 m d^{-1}), all of which are liable to reduce the rate of soil water evaporation from the underlying peats. This work also demonstrates that there are considerable inter-seasonal variations in shrinkage and swelling on such peatlands coincident with the raising and lowering of the ditchwater level (up to 4.3 cm between winter and summer).

On the more deeply drained and intensively farmed peatlands of the East Anglian Fens this work indicates that where positive water management is used in conjunction with sub-irrigation at 20 m spacings that the rate of subsidence is relatively low; ranging between 0.9 and 1.9 cm year^{-1}. It also appears that areas of predominantly fibrous peat (according to the modified von post scale) account for the upper end of these subsidence rates. Previous research has suggested that mean long-term rates of subsidence on East Anglian peatlands range from 2–4 cm year^{-1} (French and Pryor 1993, Cook 1990). This suggests the water-management strategy adopted at Methwold Fen has reduced subsidence of these peatlands.

Irrespective of the mean annual rates of subsidence the differences in the physical and hydraulic properties of the peats under historically different land-use and water-management regimes can defy expection; as more highly degraded peats can maintain equally low bulk density under saturated conditions (0.17 g cm^{-3}) relative to fibrous peats (0.12 g cm^{-3}) which have experienced increased over-burden during prolonged intensive land-use activity. Though such consolidation of more fibrous peats should, in theory, increase their WRC the saturated lateral hydraulic conductivity still appears relatively high (3.0 m d^{-1}) when compared against semi-fibrous peats under less intensive land use (2.3 m d^{-1}). This may be because these consolidated, fibrous peats from Methwold Fen have less water trapped in an immobile phase (intra-particulate porosity), such as fibres and dead-end pores, relative to the semi-fibrous peats from West Sedgemoor that have not been consolidated. This investigation also indicates that where such fibrous peats have already experienced long-term consolidation (due to intensive agricultural activities) that they still maintain considerable capacity for additional shrinkage if they are unconfined (74 per cent loss of volume when oven dried for 48 hrs at 105 ºC).

Evaluation of microbial respiration in peat microcosms suggests the rate of SOM mineralisation does not always conform to Arrhenius equation (a step increase in temperature will lead to a step increase in the rate of chemical reaction *i.e.* metabolic mineralisation of organic matter). Q_{10} values for basal respiration are in some cases negative when the atmospheric temperature is lowered from 20 ºC to 10 ºC at particular moisture contents (*e.g.* for semi-fibrous peats from West Sedgemoor experiencing a pressure potential of -0.5 m Q_{10} is -1.2 between 20 and 10 ºC but +2.1 from 20 to 30 ºC). This reduced susceptibility to mineralisation at higher temperatures is in general agreement with recent work by a number of authors on the long-term response of SOC mineralisation rate to such changes in temperature (Knorr *et al.* 2005, Eliasson *et al.* 2005, Fang *et al.* 2006). However, this work goes a stage further, to suggest that microbial mineralisation of deeper and more fibrous SOM is sensitive to temperature, but specifically to the prevailing long-term soil temperature experienced in the field, and then only within a narrow band of quite wet soil conditions (*e.g.* up to 15 µg CO_2-C g soil^{-1} hr^{-1} at 10 ºC and 70 per cent soil moisture).

Larger-scale monitoring of peat soil respiration does, however, suggest there is a reasonably high degree of temperature sensitivity in surface peats (*e.g.* on Methwold Fen surface soil cores with -0.3 m water level the rate of respiration was 0.14 g CO_2-C m^2 d^{-1} in December and continued to increase to 1.06 g CO_2-C m^2 d^{-1} by the following July). Microcosm respiratory data also suggests that the availability of alternative and simpler organic carbon substitutes that simulate root exudates (glucose) may mean that such microbial respiratory activity in surface peats are closely linked to cycles in surface vegetation growth and the release of such root exudates. Such is likely when soil moisture was controlled with a pressure potential of -0.5 m and atmospheric temperature was set at 10 ºC the West Sedgemoor peaty loam had an average basal respiration rate of 3.8 µg CO_2-C g soil^{-1} hr^{-1} but when amended with glucose under similar conditions the average rate of respiration was 17.7 µg CO_2-C g soil^{-1} hr^{-1}.

Addition of fertilizer-N also appears to exacerbate C-mineralisation, especially in deeper peats (*e.g.* when soil moisture was controlled with a pressure potential of -0.5 m and atmospheric temperature was set at 10 ºC the fibrous peat from Methwold Fen had an average basal respiration of 5.6 µg CO_2-C g soil^{-1} hr^{-1} but this increased to 10.0 µg CO_2-C g soil^{-1} hr^{-1} when the C:N ratio was lowered from the background ratio of 20:1 to 10:1).

Though qCO_2 is greater in deeper peats (*e.g.* at 0.5 m pressure potential and 20 ºC the semi-fibrous peat from West Sedgemoor had a qCO_2 of 11.5 µg CO_2-C hr^{-1} mg

Biomass-C^{-1} whilst the surface peaty loam has a qCO_2 of 6.3 µg CO_2-C hr^{-1} mg Biomass-C^{-1}) the efficiency of respiration is not reflected in the rate of mineralisation of organic matter (*i.e*. more labile sources of carbon or additional nitrogen did not have a greater effect on the rate of respiration of the deeper peats). This suggests that the soil microbial communities in deeper peats are adjusted to nutrient poor environments and cannot readily take advantage of additional resources. It also suggests that there is a lack of microbial species succession in these peats as conditions change; and indicates that these peats may not have a wide variety of microbial species in resting stages that are able to respond to more favourable conditions.

This work demonstrates there is a greater abundance of gram-negative and anaerobic bacterial species in deeper and wetter peat deposits compared with surface peats. In West Sedgemoor peats where sub-irrigation was widely spaced (40 m) the much deeper, continually inundated peats had gram-negative and anaerobic bacterial species accounting for 26 per cent of the bacterial abundance. Conversely, in the drier surface horizons they only accounted for 19 per cent of total abundance. Where 10 m spaced sub-irrigation was in place the abundance of gram-negative and anaerobic bacterial species increased to 25 per cent in the surface peats. The lack of response to changes in nutrient and environmental conditions therefore suggest that the microbes in the deeper, wetter peats are predominantly psychrophilic micro-aerophiles.

Manipulation of soil water on peat microcosms suggests that optimal soil moisture conditions do exist for microbial mineralisation of organic matter but these optimal conditions vary according to degree of peat degradation and atmospheric temperature conditions. Monitoring of soil core respiration rates demonstrates that mineralisation can be reduced with saturation of the soil (*e.g*. on Methwold Fen soil cores in July the rate of respiration was 0.76 g CO_2-C m^2 d^{-1} under saturated conditions but 1.67 g CO_2-C m^2 d^{-1} when the water table was 0.5 m below the surface). However, microcosm investigations demonstrate that optimal soil moisture conditions for mineralisation occurs at quite low pressure potentials (~0.5 m); suggesting that irrespective of sub-irrigation system the ditchwater management regime at field-scale must be carefully managed. At first glance, the field-scale pilot study of below surface respiration appears to confound this assessment. However, it is believed that the below surface respiration on more closely spaced sub-irrigation systems is greater than more widely spaced systems due to the predominance of wetland grass species and the greater availability of root exudates under wet soil conditions that prevail on the closer spaced system when the field water-table level is dropped during the summer months.

The analysis of microbial community structure under differently spaced sub-irrigation systems demonstrates that a greater abundance of gram-negative and anaerobic gram-positive bacteria exist in peats where closer spaced sub-irrigation systems have created a wetter environment. This implies that metabolic activity will not be as efficient on closely spaced sub-surface systems, unless alternative and simpler forms of organic matter are available for transformation (such as root exudates).

An empirical model of sub-irrigation water-table management (WatMod) is in good agreement with observed data, with an average R^2 of 0.81. Most importantly, this model demonstrates that a closely spaced sub-irrigation can facilitate detailed control of the water-table level and, if an appropriate ditchwater management regime is in place, the system can be very effective at mirroring the ditchwater level. It is therefore the ditchwater management regime that ultimately determines the effectiveness of the sub-irrigation system in reducing physical peat shrinkage, loss of water storage, water movement and of the rate of SOM mineralisation. The simplicity of the WatMod model means that with some detail of the physical and hydraulic properties of peat that the model can easily be used by land managers to aid the relatively accurate design of peatland sub-irrigation systems.

Comparing and contrasting the outcome of various water-table management regimes for low-lying agricultural peatlands is useful for land managers currently considering how best to achieve good management practice. However, such modelling is based on present day climate data and does not account for the changing availability of water resources in the future. To ensure longer term sustainable management of such peatland resources therefore requires an appreciation of how future climate scenarios will affect the availability of water resources.

Equally, the demand (and competition) for scarce water resources are expected to change in the future (IPCC, 2006). Such predictions assume increasing atmospheric

CO_2 concentrations will lead to warmer, drier summers and wetter winters. Agricultural peatland producers and conservationists will therefore need to assess how best to utilise their water resource allocation at different times of year. This will require an appreciation of how different water table regimes are likely to affect the rate at which peat soils degrade under different water management regimes and climate scenarios.

The European Union, under its Framework 5 (Quality of Life and Management of Living Resources) instigated a programme of research of agricultural peatland resources under the banner 'Europeat'. The Europeat project, of which this work forms a part, has investigated peatlands throughout Northern Europe and has also studied the consequence of future climate scenarios on peatland degradation. This work focuses on the consequence of climate change for low-lying agricultural peatlands in England.

10.1. Future climate scenarios

The rate of SOM mineralisation and the contribution that such mineralisation makes to atmospheric greenhouse gases affects future climate change scenarios. Such scenarios are based on changes to the concentration of atmospheric greenhouse gases and the potential of various natural and anthropogenic activities to contribute to the atmospheric carbon pool.

In considering the loss of low-lying agricultural peat soils due to mineralisation and the contribution this may make to climate change one must have an appreciation of the quantity of organic carbon stored in these soils and the peats propensity for mineralisation to CO_2 equivalents. The physical and biochemical properties of peat soils under agriculture have been shown to vary considerably and hence quantifying these soils' capacity to contribute to greenhouse gases is fraught with difficulty. Indeed, The Department of Environment (1994), when reporting to IPCC on UK climate change relied heavily on converting estimates of peat SOM deposits into SOC stocks. This was based on previously reported values of peat soils dry bulk density, SOM content and finally a standard conversion factor to calculate the organic carbon content of the organic matter. These parameters were based on the estimates of several researchers (Clymo 1983, Hulme 1986) of peat soils dry bulk density; which was put at 0.1 g cm^{-3}. However, Howard *et al.* (1994) in earlier reports based their estimates of Great Britain's peat carbon stocks on a dry bulk density value of 0.35 g cm^{-3}. This difference in calculation meant the estimated carbon stock in peats decreased from 21773 Mt of organic carbon to just 9500 Mt organic carbon. This work demonstrates that the dry bulk density of low-lying agricultural peat soils can range from 0.1 g cm^{-3} to 0.5 g cm^{-3}, depending on the type of peat, its degree of degradation and the soil water regime it experiences.

The Soil Survey of England and Wales undertook soil surveys of low-lying agricultural peatlands in the 1980s'; quantifying the peat soil deposits according to their degree of degradation and horizon thickness. Future climate change modelling could be enhanced with such information. However, analysis of such data must also take account of the relationship between the degree of degradation and the water regime at the time of sampling, as the peat matrix changes in bulk density as it shrinks and swells. Indeed, this work indicates that the void ratio decreases linearly relative to moisture ratio at very low pressure potentials (chapter 6.6.3.1: Figure 21 for Methwold Fen peats and Figure 22 for West Sedgemoor peats). It is most likely that peat deposits lying in the vadose zone will experience the greatest variation in bulk density as a consequence of the season of sampling. Such change in bulk density has implications beyond calculating peatland storage of SOM.

The soil-water regime also influences the biochemical activity in these peat soils and hence affects the rate of organic carbon loss to the atmosphere through microbial mineralisation. The most efficient form of microbial metabolism is aerobic respiration, which can only result once the air entry point of the peat is achieved. The near normal shrinkage of peat at negative pressure potentials in excess of -1.0 m suggests the relative saturation of peats increases after this point and up to pressure potentials of -40 m. It might be thought that increasing the soil moisture content beyond this to commonly proposed 60 per cent would suppress microbial mineralisation of SOM, but this work suggests that the microbial communities in deeper peat deposits thrive and have considerable capacity for metabolic activity at soil moistures much greater than this.

Though future climate scenarios vary due to a vast range of factors, such scenarios are primarily driven by assumptions about changes in the concentration of atmospheric greenhouse gases under different socio-economic situations. Some reports of climate change suggest it will lead to increased competition for scarce water resources; which will necessitate different approaches to water-management planning. If such is the case then the contribution that the mineralisation of peat soils will make to global warming is likely to vary; irrespective of the fact that recent research now suggests long-term mineralisation of SOM is not as temperature sensitive as once thought. The changes in rainfall and evapo-transpiration patterns are liable to require much greater efficiencies in agricultural water management. Two future regional climate scenarios are therefore considered to demonstrate that a change in rainfall and evapo-transpiration rates have the potential to increase soil-moisture deficit without any form of water-management intervention.

As part of the Europeat project, the Swedish Rossby Centre provided regional climate scenario data to all six member states of the project [27], using the global ECHAM4/OPYC3 model (Raisanen *et al*., 2004). The data provided has its foundation in the Inter-governmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES), drafted by Nakicenovic *et al*. (2000). In total, three scenarios were run (Table 123 and Table 124, appendix I); a 30-year control from 1961-1990 and two 30-year runs (based on the SRES A2 and B2 emission scenarios) from 2071–2100 (Figure 59).

The A2[28] scenario assumes relatively large (in comparison with most of the other SRES scenarios) and continuously increasing emissions of the major anthropogenic greenhouse gases CO_2, CH_4 and N_2O, whilst the B2[29] scenario also includes increases

[27] Europeat Project member states: England, Germany, The Netherlands, Norway, Poland and Sweden.

[28] The A2 scenario describes a very heterogeneous world. The underlying theme is one of self-reliance and preservation of local identities. There is continuous increase in global population. Economic development is regionally and the economic growth per capita and technological changes are slower and more fragmented than other scenarios.

[29] The B2 scenario describes a world in which local solutions to economic, social, and environmental sustainability are emphasised. Global population increased at a lower rate than A2. Economic development is intermediate with a focus on local and regional development. The scenario is oriented toward greater environmental protection and social equity.

in CO_2 and CH_4 emissions, but at a lower rate; in the bottom midrange of the SRES scenarios.

Figure 59 a-c each depict historical (observed and modelled) and predicted future climate scenarios for the South-Western region and Figure 59 d-f depict the same type of climate data for the East Anglian region of England.

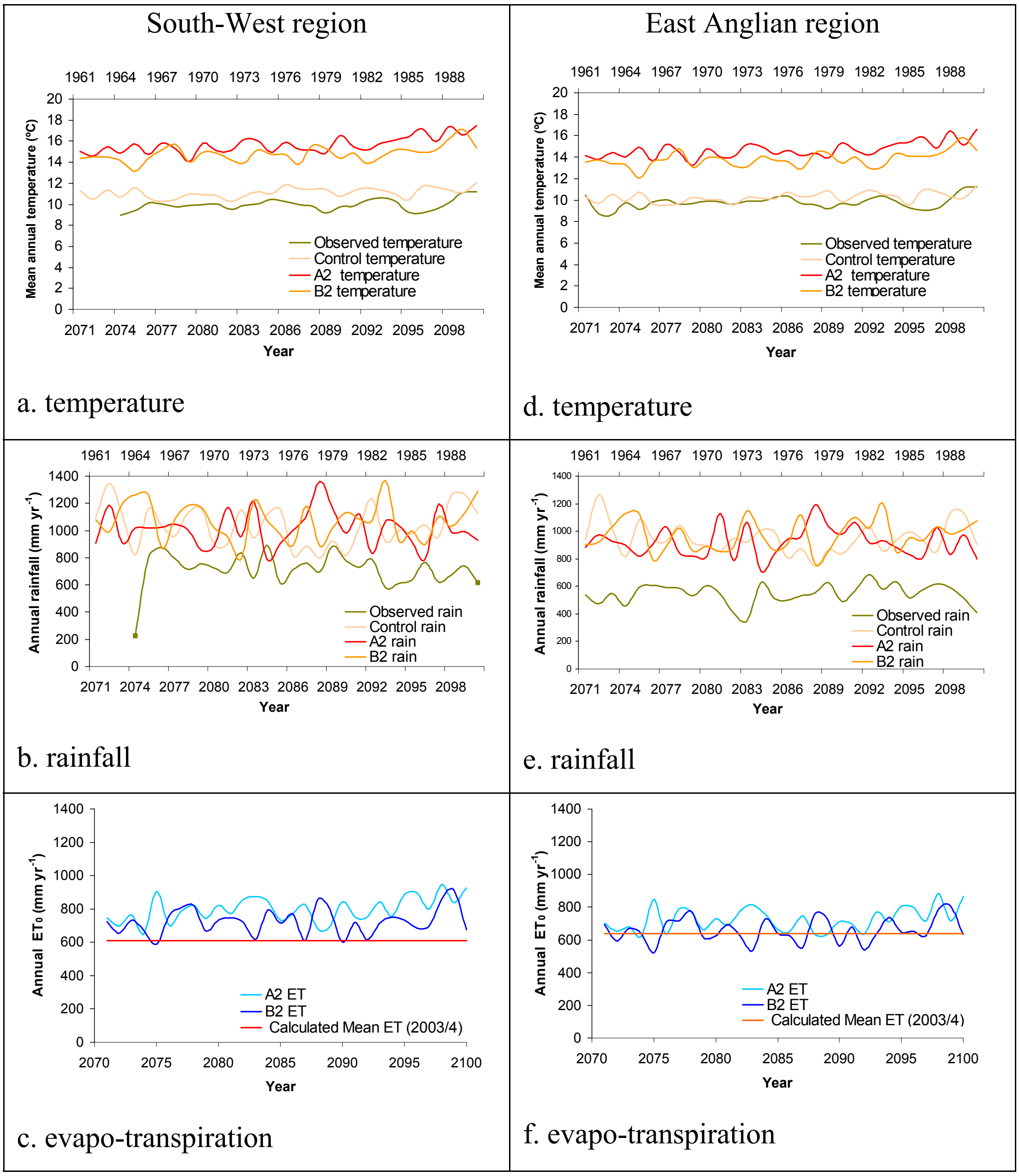


Figure 59: Observed historical (1961-1990) and SRES modelled Control, (1961-1990), A2 and B2 climate scenarios (2071-2100).

There is a relatively good fit between observed and historical atmospheric temperatures for both research regions (Figure 59 'a' and d), with the modelled (Control) situation marginally over-estimating atmospheric temperature. Both A2 and B2 scenarios predict that the South-Western region will be warmer than the East Anglian region. Both A2 and B2 scenarios also indicate that by 2071 atmospheric temperatures will be, on average, 3 ºC greater than the historical (1961-1990) mean for both regions. The A2 scenario predicts an environment that is warmer than the B2 scenario and generally both scenarios predict that temperatures will continue to rise by a further 2 ºC over the 30 years between 2071 and 2100.

In terms of rainfall (Figure 59 b and e), there is considerable deviation of the Control data (1961-1990) from the historically observed data (1961-1990). The Control over-estimates the rainfall, on average, by 1.4 times (range 0.98-1.9). Irrespective of this over-estimation, the relative change in rainfall between the Control and the A2 and B2 scenarios suggests both will result in much drier summers and much wetter winters in the future, with the A2 scenario predicting the driest summers and wettest winters (Table 125 to Table 130, appendix I). However, over the 30 years period of the modelling there does not appear to be any continued increase in the annual cumulative rainfall.

The rate of evapo-transpiration (Figure 59 c and f), when compared against data from 2003/4 (chapter 8.6.1) suggests the cumulative rate of annual evapo-transpiration will be marginally greater in the future and continue to increase marginally up to 2100. Generally, the A2 scenario results in a greater increase in evapo-transpiration across both regions, but to a slightly greater extent in the South-Western region.

Overall, the future scenarios predict a warmer environment with drier summers and wetter winters and greater rates of evapo-transpiration. This suggests that future demand for scarce water resources management during summer months will require greater efficiencies of use. This is especially true of low-lying agricultural land, where intensive agricultural operations place a heavy burden on water resources.

Whilst climate scenario data provides an appreciation about future temporal and spatial availability of water resources, such scenarios alone do not elucidate the effect that changing water resource availability will have on the degradation of agricultural peatlands. Equally, knowledge of peat physical and hydraulic properties under changing soil moisture conditions needs to be coupled to biochemical mineralisation of peat SOM if water-management planning is to enhance peatland sustainability. Climate scenario data therefore needs to be analysed with soil hydrology models that can account for shrinkage and swelling of these soils under changing pressure potentials, and hydrological models that are also capable of coupling with nutrient dynamics models that can analyse and quantify the effects of soil water regime on the physical and biochemical degradation of peat.

10.2. Modelling the future sustainability of low-lying agricultural peatlands

Complex process orientated hydrological models; such as the SWAP, can be coupled with process orientated nutrient dynamic models; such as ANIMO, to predict the consequence of changing soil moisture regimes on mineralisation of SOM. Such process orientated models, when used in conjunction with future climate scenarios allow the consequence of changes in climate to be considered.

As part of the Europeat project, The Netherands (Alterra) developed the link between the hydrological model SWAP, and the nutrient dynamics model, ANIMO, specifically to investigate the degradation of agricultural peat soils. What follows is a brief outline of the SWAP and ANIMO models and how they are used in this thesis to assess future sustainability of low-lying agricultural peatlands in England.

Both SWAP and ANIMO have the benefit of compartmentalising the soil profile into numerous layers. This means that SWAP can solve Richard's equation (Equation 32) for flow in the unsaturated and saturated zones simultaneously in very small layers; accounting for the changing physical properties of each peat horizon. The SWAP model also accounts for the effect of shrinkage and swelling on soil moisture content and the profile compartmentalisation therefore incorporates the differences in peat type throughout the soil profile. The process orientated base of SWAP also means that changes in soil moisture allow changes in soil temperature to be determined from atmospheric temperature.

$$\frac{\partial\theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S_a(h)$$

Equation 32: Richard's equation for flow in variably saturated soils
where θ is volumetric water content ($cm^3\ cm^{-3}$), K is the hydraulic conductivity ($cm\ d^{-1}$), h is the soil water pressure head (cm), z is the height above a known datum (cm), t is time (s) , S_a is the soil water extraction rate by plant roots ($cm^3\ cm^{-3}\ d^{-1}$) and C is the soil water capacity δθ/δh (cm^{-1}).

SWAP uses the same parameters described for WatMod (i.e. predefined lateral and vertical boundary conditions, soil hydraulic functions (water retention according to van Genuchten (1980), Rainfall, actual and potential evaporation and transpiration according to Penman-Monteith equation (Monteith, 1965) and the Ernst-Hooghoudt drainage equations).

ANIMO solves nutrient leaching from the soil by taking the compartmentalised water-balance output from SWAP to make water quality calculations. The transport of soil nutrients with such water fluxes is solved for each time step and for every compartment of the model using the equation:

$$\frac{\partial\theta c}{\partial t} + \rho_d\frac{\partial X_e}{\partial t} + \rho_d\frac{\partial X_n}{\partial t} + \rho_d\frac{\partial X_p}{\partial t} = \frac{\partial}{\partial z}\left(qc - \theta D_{dd}\frac{\partial c}{\partial z}\right) + R_p - R_d - R_u - R_x$$

Equation 33: Transportation of soil nutrients in solution, according to Renaud *et al*. (2004).
where:
θ is the volume fraction of liquid ($m^3\ m^{-3}$)
'c' is the mass concentration in the liquid phase ($kg\ m^{-3}$)
t is time (days)
Xe, Xn and Xp are contents ($Kg\ m^{-3}$) in the solid phase of the soil
Z is the depth of soil (m)

Q is the water flux ($m^3\ m^{-2}\ d^{-1}$)
D_{dd} is the apparent dispersion coefficient ($m^2\ d^{-1}$) of a solute in liquid phase
R is a sink or source term expressed as a volumetric mass rate of the substance (kg $m^{-3}\ d^{-1}$). R_p is a source for production; R_d is a sink for decomposition; R_u is a sink for crop intake, and; R_x is a sink for lateral drainage or infiltration.

The transformations of soil nutrients from organic matter to mineralised fractions are solved for each time step and for every compartment of the model using the equation:

$$k = f_{ae,OM}\ f_T\ f_\theta\ f_{pH}\ k_{ref}$$

Equation 34: Transformation of soil nutrient, according to Renaud *et al*. (2004)
where k_{ref} is the rate coefficient value for fresh organic materials, dissolved organic carbon, dissolved organic matter, root exudates, and humus biomass. The other variables are environmental multiplication factors that account for reduced aeration (f_{ae}), drought stress (f_θ), temperature (f_T) and pH (f_{pH}).

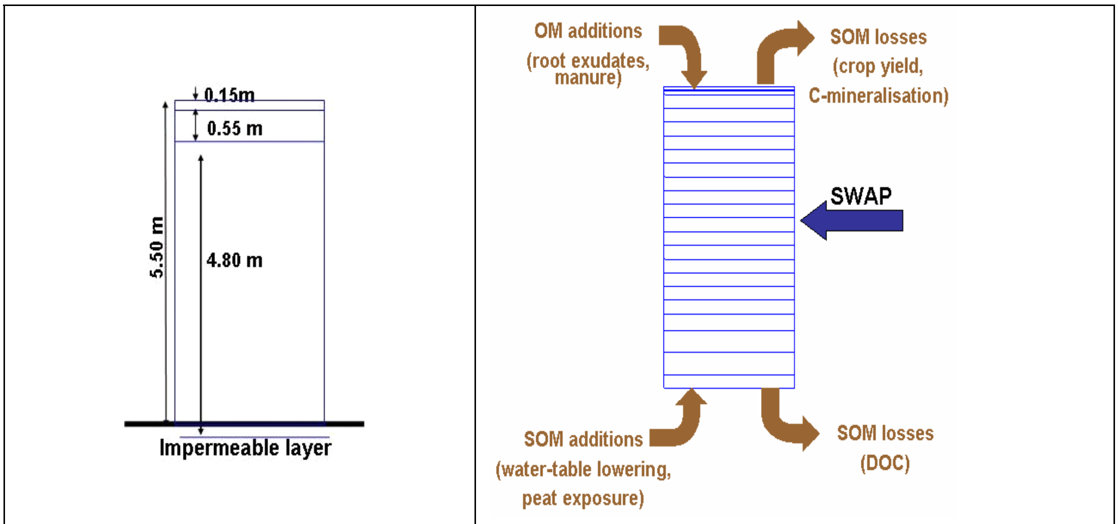
A fuller account of the processes involved in carbon and nitrogen transformations can be gained through Renaud *et al.* (2004). ANIMO is a process based model and the rate of biochemical mineralisation of SOM is determined according to soil moisture content defined by Bril *et al*. (1994), temperature effects according to the Arrhenius equation and pH effects according to Renaud *et al*. (2004). ANIMO has the benefit that it differentiates between additions of SOM from different types of farm activity (manure and fertilizer application) and from exposure of fresh SOM as the water table moves up and down and from root exudates. Equally, it considers SOC losses due to farm activities (crop yield), C-mineralisation and dissolved organic carbon leaching.

10.2.1. A case study of West Sedgemoor.

The raised water level management plan (Tier 3) in operation at West Sedgemoor and the high inter-seasonal capacity for subsidence suggest this peatland has considerable potential to degrade if the land-use and/or the water-management plan changed.

The SWAP 3.03 model (Kroes and van Dam, 2003) was coupled with ANIMO 4.0 model (Renaud *et al.*, 2004) to investigate the consequence of water-table management on mineralisation and associated subsidence at West Sedgemoor under differently spaced sub-irrigation systems. The physical and hydraulic input parameters used in SWAP are from data in chapter 6.6, boundary conditions are from soil survey findings (chapter 5.5.2) and nutrient inputs to ANIMO are based on Tier 3 management prescriptions on nutrient additions outlined in chapter 2.4.2. Cattle stocking density on the West Sedgemoor research area is low and the standard definition of low stocking density is 1.4 cattle ha^{-1}. This stocking density was therefore used in conjunction with RB209 (MAFF, 2000) to estimate approximate additions of organic matter as slurry. The calculated value of 1033 kg organic matter ha^{-1} month^{-1} (dry weight) was used to determine the Nitrogen and Phosphorus additions, as slurry, to the West Sedgemoor peats. These additions were 8 kg ha^{-1} month^{-1} Nitrogen and 3.2 kg ha^{-1} month^{-1} Phosphorus (in contrast, RB209 recommends 200 kg ha year^{-1} for intensive agricultural activity on peat soils).

The soil profile for both models was compartmentalised (discretisation) according to advice from Kroes and van Dam (pers comm') and shown in (Figure 60).



a. SWAP discretisation (peat type)   b. ANIMO discretisation

Figure 60: Compartmentalisation of the soil profile for West Sedgemoor peatlands.

The water-table output from SWAP was calibrated against the observed water-table data and also compared against the more empirical WatMod Model (Figure 61).

Figure 61 ‘a’ depicts the Control (ditches at 200 m spacing); b is where 10 m spaced sub-irrigation is used; c is 25 m spaced and d is 40 m spaced.

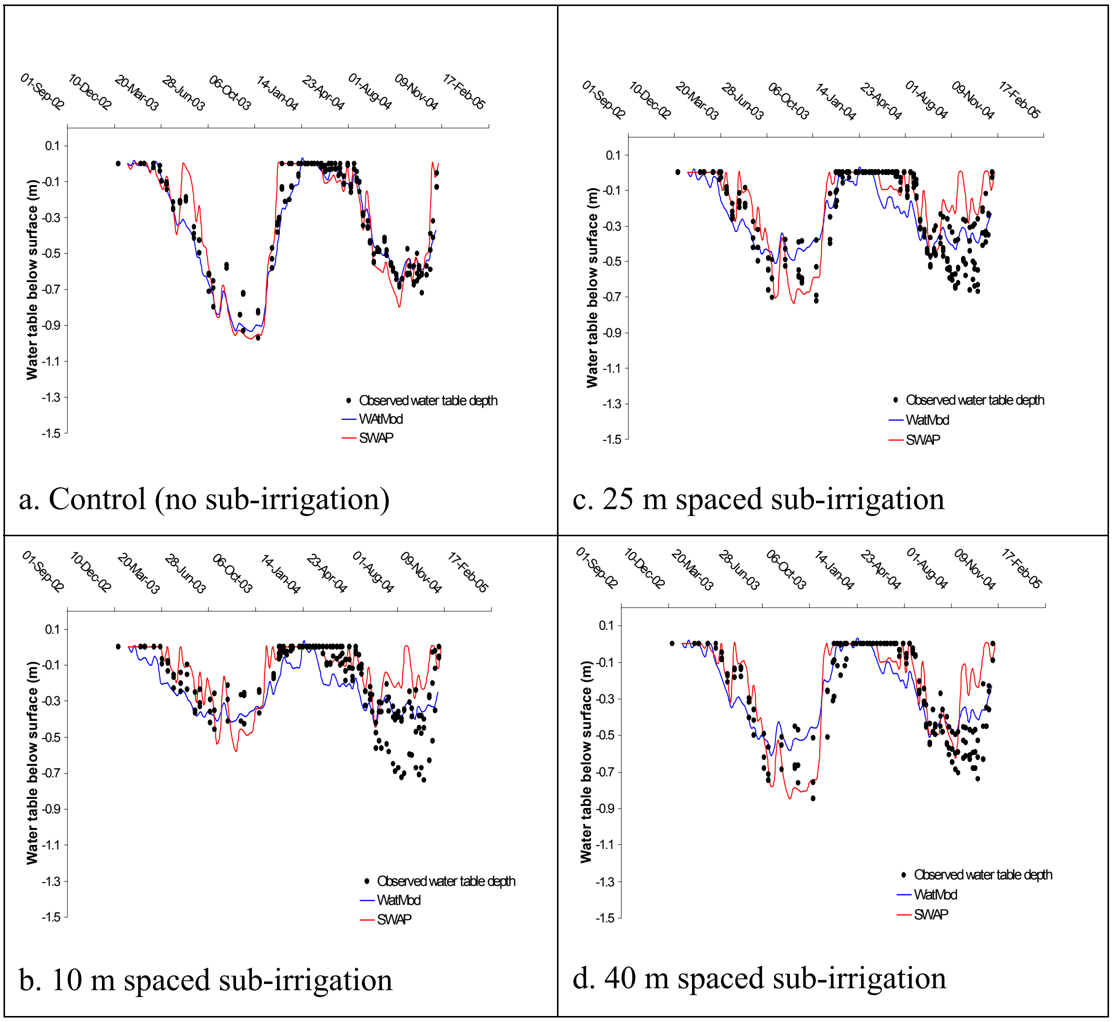


Figure 61: Agreement between the SWAP and WatMod models and observed water-table data.

Figure 62 illustrates the relatively good fit between SWAP and the observed data (mean R^2=0.61). Although the modelling efficiency does decrease with more closely spaced irrigation interval, all modelling efficiencies still indicate SWAP performs well[30]. That said, the much simpler WatMod model (chapter 8) demonstrated an even better mean fit to the observed data (mean R^2=0.81), with even higher modelling efficiencies than SWAP[31]. However, WatMod’s inability to compartmentalise the soil profile according to soil physical properties precludes it’s coupling with ANIMO.

[30] The SWAP modelling efficiencies (Smith *et al*., 1996) were 0.81 (200 m intervals); 0.55 (40 m intervals); 0.35 (25 m intervals) and; 0.23 (10 m intervals).

[31] Refer back to Chapter 8 footnote 23.

Even though Figure 62: Correlation between SWAP and observed water table levels for differently spaced sub-irrigation systems at West Sedgemoorthere are some discrepancies between modelled and observed data these previously described differences are believed to result from blockages in some of the sub-irrigation pipes and are not believed due to errors in model calculation. SWAP's capacity to compartmentalise the soil profile means that when coupled with ANIMO it can predict mineralisation rates and hence allow estimates of subsidence to be achieved.

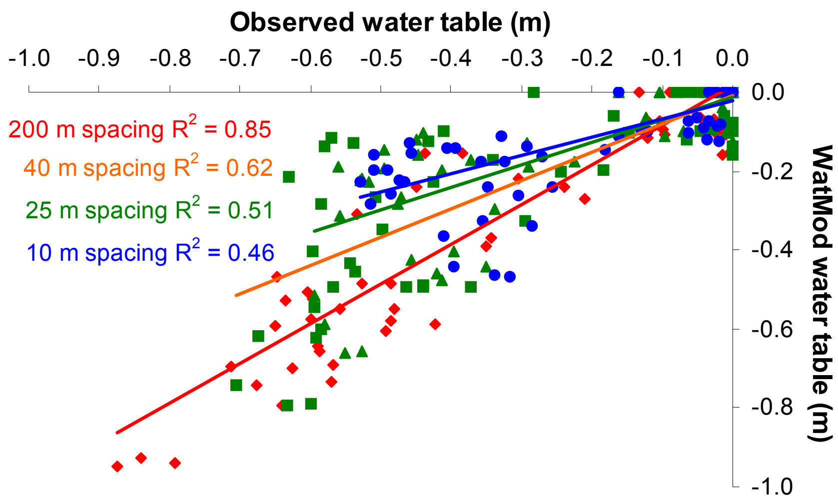
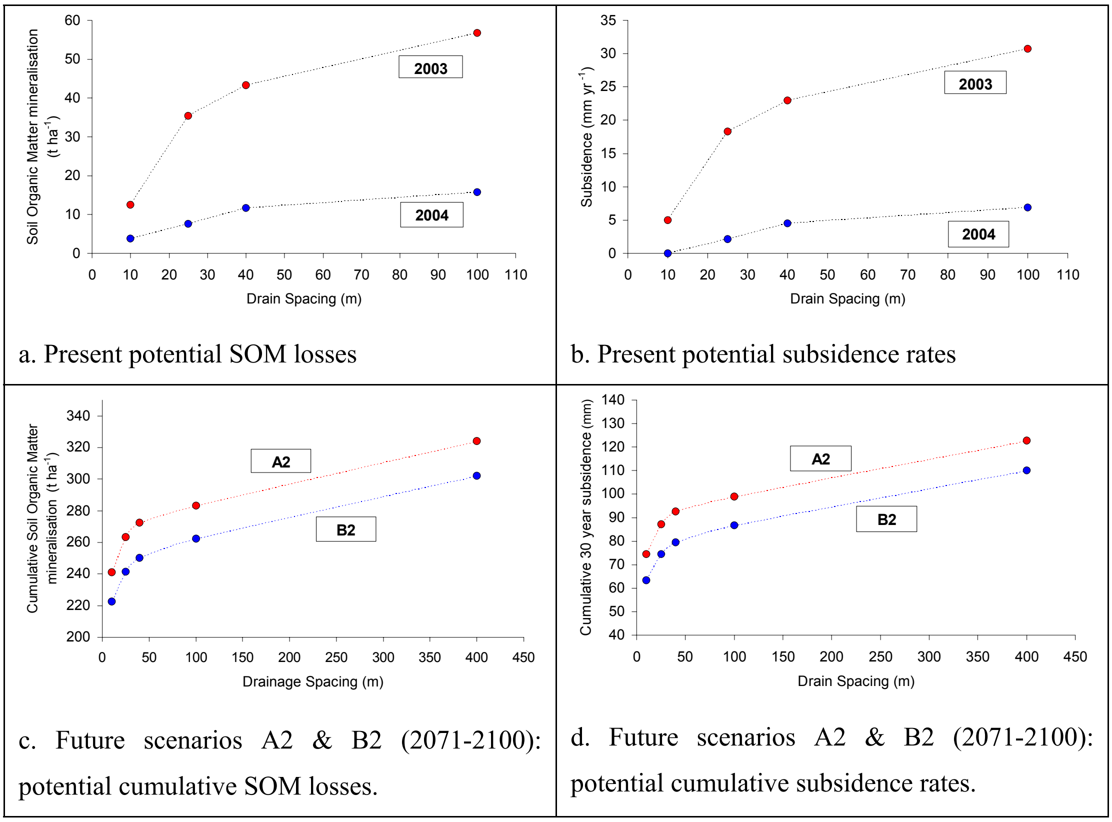


Figure 62: Correlation between SWAP and observed water table levels for differently spaced sub-irrigation systems at West Sedgemoor

Determining the difference between the ANIMO input parameters of organic matter addition (from agricultural additions of fertilizer) and loss (due to process based mineralisation), allows an estimation of the theoretical rate of subsidence of West Sedgemoor peatlands under different water-management regimes (using an estimated mean dry bulk density of 113 kg m^{-3} (Equation 52, appendix J) and a mean SOM content of 66 per cent (Equation 53, appendix J - determined from the findings of chapter 6.6)).

Figure 63 depicts the modelled loss of SOM due to mineralisation under different water-management systems and the theoretical change in surface elevation resulting from such mineralisation. Figure 63 'a' and 'b' show theoretical rates of organic matter mineralisation and peatland subsidence due to mineralisation in 2003/4 for West Sedgemoor. Figure 63 'c' and 'd' show theoretical rates of SOM mineralisation and peatland subsidence due to such mineralisation based on future climate scenarios A2 and B2 at West Sedgemoor (section 10.1). The output from SWAP-ANIMO determined SOM gains and losses are given in appendix J (Figure 65 to Figure 68 for 2003, Figure 69 to Figure 72 for 2004 and Figure 73 to Figure 77 for future scenarios A2 and B2).

Figure 63 'a' suggests that the much warmer and drier conditions experienced during 2003 could have led to much higher rates of SOC mineralisation (10-55 t ha^{-1}) than in 2004 (3-15 t ha^{-1}) but that the rate of mineralisation would have been toward the lower end (reduction of 550 per cent) if the present Tier 3 ditchwater management regime was used in conjunction with sub-irrigation at 10 m spacings. Such a water-management strategy in a drier year could reduce annual subsidence by 2.5 cm $year^{-1}$ whilst in a normal year (2004) such management could reduce subsidence by up to 0.5 cm $year^{-1}$ (Figure 63 b). Where future climate scenarios are considered they point toward cumulative organic matter mineralisation between 220 and 330 t ha^{-1} over 30 years (Figure 63 c) resulting in cumulative subsidence of between 60 and 120 mm over the 30 years of the simulation (Figure 63 c). The A2 scenario predicts the greatest rate of organic matter loss and subsidence, which one would expect, given the warmer and drier summers of the A2 scenario. The mean annual organic matter mineralisation rates for both climate scenarios lies between 7-11 t ha^{-1} and subsidence between 2-4 mm $year^{-1}$, which is quite similar to the range of values predicted for 2004. Irrespective of climate scenario, closely spaced sub-irrigation could reduce the annual rate of subsidence by 2 mm $year^{-1}$. If the warmer and drier A2 scenario prevailed then, irrespective of sub-irrigation system spacing, mineralisation rates would lead to an increase in subsidence of 0.3 mm $year^{-1}$ which, over the short term, appears to be minimal. However, the cumulative consequence over 30 years would be a loss of 9 mm of peat.



a. Present potential SOM losses

b. Present potential subsidence rates

c. Future scenarios A2 & B2 (2071-2100): potential cumulative SOM losses.

d. Future scenarios A2 & B2 (2071-2100): potential cumulative subsidence rates.

Figure 63: SWAP-ANIMO predicted mineralisation and estimated subsidence due to mineralisation of West Sedgemoor peats under water-management systems (sub-irrigation spacing).

There are quite large scales of difference in rates of mineralisation between the field and soil core measurements and the output of SWAP-ANIMO. Scaling-up the maximum rate of field respiration determined in chapter 9.6.1 suggests a maximum SOM loss of 2.67 t ha^{-1} year^{-1}, which is in agreement with Nieven *et al.* (2005). Scaling up the maximum rate of mineralisation from soil core respiration, suggests a maximum 6.0 t ha^{-1} year^{-1} of SOM would be mineralised, which is in agreement with Moore and Dalva (1997). For 2003 the SWAP-ANIMO predicted mineralisation rates range from 10 to 55 t ha^{-1} year^{-1}. The upper end of this range is comparable with the upper end of peat mineralisation reported by Nieven *et al.* (2005) but does not come close to the very high range of values reported by De Busk and Reddy (2003).

The SWAP-ANIMO output for 2004, which ranged from 3 to 15 t ha^{-1} year^{-1}, and the future mineralisation rate scenario (2071-2100), which ranged of 7 to11 t ha^{-1} year^{-1}, both appear more comparable with the aforementioned measured data.

ANIMO is a process orientated model (*i.e*. changes in the rate of organic matter mineralisation assumes optimal soil moisture conditions at 58 per cent water filled pore space (Bril *et al.*,1994). The rates of mineralisation also conform to the Arrhenius equation on temperature dependence of the rates of reaction. The findings reported in chapter 7.5; that soil microbes in these peats appear to function optimally at moistures far in excess of 58 per cent suggests that mineralisation rates may not follow the generalised process orientated rate of reaction used by ANIMO. It seems likely that the adaptation of soil microbes to niche environments means they are unlikely to respond so readily to the prescribed optimal soil moisture or follow a predefined rate of reaction according to a change in temperature. This is especially true if the environment is filled with specialist microbes where no succession in community is likely. This would tend to agree with Feller and Gerday (2003) report; "*…that optimal growth temperatures of specific microbial communities do not necessarily coincide with optimal temperatures for metabolic processes"*.

Irrespective of the differences in the scale of mineralisation rate, the results from SWAP-ANIMO modelling do tend to agree with the general conclusion of this work on field-scale water-table management and mineralisation from soil cores. Closer spacing of sub-irrigation and higher water-tables reduces the rate of organic matter mineralisation. However, the theoretical rate of annual subsidence due to mineralisation for 2003 (dry year) seems rather large relative to the long term change in surface elevation determined from historical reports and topographic surveys of West Sedgemoor undertaken during this work (chapter 5.5.1). This implies that future A2 and B2 scenarios are liable to have over-estimated the rate of organic matter mineralisation. This may be due to differential availability of alternative sources of organic carbon compounds such as root exudates at West Sedgemoor. Greater availability of such root exudates would off-set the mineralisation rate of SOM.

Overall, the SWAP-ANIMO model demonstrates the relative benefits of raising the water-table level and improving control over water-table fluctuation; as the rate of peatland subsidence due to mineralisation decreases dramatically when sub-irrigation systems are closely spaced and ditch water tables are held high. Similarly, the work of earlier chapters demonstrates that the degree of physical shrinkage of peat can be minimised and water storage and flow improved when the same soil moisture regime is imposed.

11. Conclusions and recommendations

11.1. Conclusions

Soil water management regimes do exist that can enhance the sustainability of lowland agricultural peatlands under different land-use.

The effect of various land and water-management regimes for the sustainability of various peatlands, and of the smaller scale effects of changing soil moisture conditions for the rate of biochemical degradation and loss of different peat soils, are summarised below.

1. **Land-use and water management have exerted an influence on the magnitude of peat soil degradation.**

- Subsidence of low-lying agricultural peatland, where water management has been employed, occurs at a greater rate on intensively farmed peatlands relative to peatlands under grass, where the dominant land use is extensive grazing.

- Intensively farmed peatlands employing a water management strategy experience a lesser rate of subsidence than those without a water management policy.

- Where a peatland is shallow and has experienced long term drainage there is a greater propensity for degradation of surface horizons under intensive land use.

- Where Fen Clay underlies shallow peat deposits, there is an increased likelihood of acidity and a build up of ochre in drainage channels and sub-surface pipes. This can reduce the efficiency of water management.

- Intensive drainage practices can lead to greater consolidation of deeper peat horizons, especially where such horizons have maintained some structural integrity, due to having experienced less intensive biochemical degradation.

2. The soil water regime does influence the physical and biochemical properties of peat soils.

- Although high water-tables can maximise water storage potential and movement of water through peat soils, pristine fibrous peats that are subject to intensive land-use can experience greater loss of water storage capacity than more humified peats that have experienced less intensive land-use.

- Humified peatlands where such low intensity land-use exists are equally susceptible to shrinkage as fibrous peats under more intensive regimes, but only if they are subject to increasing pressure potentials. This potential for changes in even humified peats demonstrates that water-management practices can still have a negative effect on water storage and flow in humified peatlands and that the degree of peat degradation is not the only factor that dictates the propensity of a peat soil for further degradation.

- The considerable variability in peat soil hydrology and geochemistry between peats at different stages of degradation and under different land uses impacts on soil microbial biomass and community structure and therefore affects the rate of soil organic matter mineralisation.

- The study of soil quality (microbial activity and biodiversity) indicates that maintaining very high soil moisture conditions can minimise microbial metabolisation of organic matter in surface peat soils.

    - Very low pressure potentials (close to saturation) can reduce SOM mineralisation in deeper peat horizons. Deeper peat horizons do, however, appear more prone to optimal microbial metabolic activity where there are even small increases in pressure potential.

    - It appears that surface peat horizons may be more susceptible to increased microbial metabolisation with increased atmospheric temperature. Such increased activity may also be due to greater microbial biodiversity and lower C:N ratios in surface peats.

- Deeper peats are less vulnerable to mineralisation at higher atmospheric temperature but are also liable to experience greater rates of mineralisation at the prevailing long-term soil temperature (i.e. 10 ºC), but only if the water table is dropped to a depth where pressure potentials approach 0.5 m.

- The difference in metabolic activity of deeper peats may be due to increased C:N ratios and the predominance of specialist microbes that are unable to take greater advantage of nutrient availability unless their narrow optimal soil moisture conditions are achieved.

3. **Differing land-uses exert an influence on the magnitude of organic carbon loss, as measured through gaseous exchange of carbon dioxide.**

- Rates of soil organic matter mineralisation can be masked by the presence of surface vegetation. Such vegetation can provide alternative sources of organic carbon for soil microbial activity. Indeed, the ready availability of such an alternative source of organic carbon is likely to reduce the biochemical mineralisation of soil organic matter in upper horizons of peat soils.

4. **Higher water-tables can decrease changes in the physical and biochemical integrity of peat soils and therefore reduce the degradation and loss of peat.**

- The successful implementation of a wetter water management regime on peatlands can influence the physical properties of even highly degraded peat and, if complete inundation of the soil profile is achieved, the structural degradation of peat soil can be reduced (e.g. reduced bulk density and increased porosity).

- Even the partial aeration of a moist peat profile can lead to higher rates of biochemical mineralisation of such soils and, where a higher water table regime is imposed in such peats, even a temporary lowering of the ditchwater level can lead to optimal soil moisture conditions that in turn create an optimal environment for increased aerobic microbial activity.

5. **Optimal water-management scenarios exist that can decrease peat soil degradation whilst having minimal impact on land-use.**

- A combination of ditchwater management and sub-surface irrigation can enhance field water-table levels and improve the overall sustainability of low lying agricultural peatlands if the management regime maximises the period of complete peatland inundation.

- Such a management regime can improve peatland sustainability by facilitating the suppression of biochemical degradation of soil organic matter. However, the method of installation and spacing of such sub-irrigation systems has a strong bearing on its efficiency.

- The successful implementation of such a water management regime is ultimately dependent on appropriate management of ditchwater levels.

- Empirical modelling can be used to investigate such water-management practices provided there is knowledge of basic peat soil properties and regional climate characteristics.

    - Such models affirm that water-management intervention can become limited by the design of ditchwater control and sub-irrigation systems.

    - Such models are also simple enough to be employed by end-users and therefore have the potential to aid future peatland water-management planning.

11.2. Recommendations

The ideal water-management scenario is one where both physical degradation and biochemical mineralisation are minimised. The used of ditchwater levels held close to the soil surface, in conjunction with sub-irrigation installed at 10 – 25 m spacings will ensure field water tables are held close to the surface. This will minimise physical consolidation and shrinkage of peat and will reduce aerobic microbial mineralisation of SOM. Equally, the presence of surface vegetation may provide an alternative source of organic carbon in the form of root exudates. This will reduce the microbial mineralisation of SOM. However, given the requirements of crop production, grazing, land access and the capacity of peatlands to prevent flooding by providing additional winter water storage the alternative water-management scenario is still to install ditchwater control and sub-irrigation systems at 10 – 25 m intervals but to control the ditchwater system according to land access requirements. Maintaining field water tables within 0.3 m of the soil surface during summer months would minimise physical consolidation and shrinkage that are liable to occur with wider spaced systems (due to evapo-transpiration demand) whilst simultaneously ensuring crop water requirements are met and that grazing animals do not do excessive damage. During winter months lowering the field water table to within 0.5 m of the soil surface would still keep physical consolidation to a minimum whilst also allowing land maintenance operations and providing for flood storage. However, more fibrous peats would be prone to greater metabolic activity during such periods and raising the field water table during periods where land access is not required would be beneficial. Equally, sowing some form of hardy surface vegetation cover may reduce microbial reliance on SOM as a source of carbon.

11.3. Future work

There are a number of areas where additional knowledge of peatland resources could aid future water-management planning.

- The long-term monitoring of individual peat horizon subsidence under different water-table regimes. The effectiveness of such monitoring has already been demonstrated in Holland (Schothorst, 1977) and Poland (Slatyowizc, unpublished). The method of monitoring is simple and employs individual ‘winged’ gauges. These are installed in individual peat horizons and measured against a permanent reference point sunk into underlying mineral horizon. Such monitoring could improve understanding of longer term inter-seasonal and inter-annual changes in surface elevation.

- Investigation of the long-term effects of wetting and drying cycles on the hysteretic properties and mineralisation rates of different peat soils could elucidate the importance of the temperate UK climate on peat sustainability.
- More detailed study of the importance of SOC losses from peat soils as dissolved organic carbon and methane.
- Research of peat soil microbial communities' metabolic responses to root exudate availability could aid understanding of the relative benefits of peatland conversion to pasture rather than intensive crop production.
- Detailed investigation of changes in peat soil microbial community structure over time, both with land-use, soil moisture regime and depth of peat could improve understanding of how peatland microbial communities respond to seasonal variations in soil moisture stress and how this affects their capacity for SOM mineralisation.

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Appendices

A Historical management of low-lying agricultural peatlands

A.1 The East Anglian Fens

Small 'islands' in the Fens were colonised by the monasteries as early as the 12th – 14th centuries and small-scale agriculture was practiced, though the drainage schemes in place were not integrated. After 1536 the dissolution of the monasteries resulted in a slow decline in the potential of the land. However, by 1630 there was a conviction that 'recovery' of the fertile soils of Fens constituted a sound economic proposition, because of their proximity to London. This led to the concept of a unified drainage strategy and creation of the 'Bedford Level Drainage Venture'. A Dutch engineer, Vermuyden, was contracted to execute the 'Great Level' project, which was initially satisfied in 1637, with the caveat the reclaimed areas would be 'summer grounds only'. Only 40 years later records show that the rate of peat wastage was already being noticed (Darby, 1940). With the introduction of the enclosures act and further significant improvements in agricultural yield even greater demands were put on the land. The introduction of steam pumps in 1820 to aid drainage increased the rate of subsidence further and by 1913 the efficiency of the system was such that the rate of peat shrinkage and wastage meant the average lift required to pump water from the land into the river had increased to over 15ft (an increase of almost 6ft since the introduction of steam). With the advent of the world wars government aid meant that many districts upgraded their pumping systems – resulting in an even greater rate of drainage and subsequent peat wastage.

A.2 Somerset Levels and Moors.

Though attempts at drainage date back to the 17th Century it was only during rapid advances in agriculture that many of the lowland marshes (levels) were drained, however, little change occurred in the many peat moors that existed until the 18th/19th Century, as peatland drainage proved too difficult. Overall, these peat moors were only used for common pasturing during the summer months, when floodwaters receded. Kings Sedgemoor, which lies in the middle of the area, was drained after the Drainage Act (1780), whilst further south the drainage of West Sedgemoor occurred between 1810–1816. Even after the introduction of the Somerset Drainage Act (1877) and subsequent improvements post 1939 the winter flooding remained an issue up until the 1960s.

B Soil classification

B.1 World Reference Base for soil resources (WRB).

The WRB defines ‘soils’ by the vertical combination of soil horizon, properties and/or characteristics occurring within a defined depth and by the vertical organisation of soil horizons. Thus the WRB classification refers to unambiguous diagnostic horizons.

The first set of the WRB is the Histosols and deal with all soils of organic origin. The latter 9 sets focus on mineral soils and so are not dealt with further, except in qualification of the *Histosol* set.

Definition of *Histosols*

Soils, having a histic or folic horizon, and either 10 cm or more thick from the soil surface to a lithic or paralithic contact; or 40cm or more thick and starting within 30cm from the soil surface; and having no andic or vitric horizon starting within 30cm from the soil surface.

The Reference Soil Group of the *Histosols* comprises of soils formed in ‘organic soil material’. However, there is considerable variety within this class, given that the conditions under which such soils develop range from arctic to tropical and from upland to lowland. Similarly, the type of material from which peats develop range from mosses, reeds and sedges to woody material. As there is such a variety of development conditions and types of peat parent material, it is not surprising to find that there are a whole variety of peat types, each having developed in different ways and have significantly different physical and biochemical facets. An interesting physical phenomenon of which is the likelihood of anistrophic behaviour in peats, even with only small spatial variation (vertical or horizontal), as noted by Parent and Ilnicki (2003).

The WRB defines a Histic horizon as:

“a surface horizon, or a sub-surface horizon occurring at shallow depth and consisting of a poorly aerated organic soil material”.

The diagnostic criteria for a histic horizon is:

either – 30 % organic matter (18 % organic carbon, by weight) or more if the mineral fraction consists of 60 % or more clay;
or – 20 % organic matter (12 % organic carbon by weight) or more if the mineral fraction has no clay;
or - a proportional lower limit of organic carbon content between 12 and 18 % if the clay content of the mineral fraction is between 0 and 60 %.
The organic matter content must be more than 35 % (20 % organic carbon) if present in materials typical for andic horizons, and
saturation with water for at least one-month in the majority of years (unless artificially drained); and
thickness of 10 cm or more.

A histic horizon less than 20 cm thick must have 20 % or more organic matter when mixed to a depth of 20 cm.

Also of importance is that peats' have/are not necessarily developing without influence of other soil types. Driessen *et al*. (2001) state that permafrost affected Histosols are associated with other WRB soil reference groups like Cryosols and soils with stagnic properties; like the Gleysols and, in temperate-sub arctic transitional zones, with Podsols.

Examples of 'qualifiers' that are specific to the histosol soil reference group:

Rheic histosols: Having a water regime conditioned by surface water
Ombric histosols: having a water regime conditioned by surplus precipitation during most of the year.
Sapric histosols: having, after rubbing, less recognisable plant tissue than 1/6 (by volume) of the organic soil material.
Fibric Histosols: having more than 2/3 (by volume) of the organic soil material consisting of recognisable plant tissue.
Folic Histosols: having a folic horizon

The above classification does not prevent soil profiles classified within the Histosol soil group from having characteristics of the other soil groups within different master horizons. As is the case at Westmoreland, where a Calcic horizon is evident in the soil profile.

Common soil units:
Glacic, Thionic, Cryic, Gelic, Salic, Folic, Fibric, Sapric, Ombric, Rheic, Alcalcic, Toxic, Dystric, Eutric and Haplic.

after Driessen *et al.* (2001).

B.2 The England and Wales Soil Survey.

To qualify for major soil group 10 soils must meet both the following criteria:
Either more than 40 cm of organic material within the upper 80 cm of the profile, or more than 30 cm of organic material resting directly on bedrock or skeletal material.
No superficial non-humose mineral horizons with a colour value of 4 or more that extend below 30 cm depth.
At soil group level there are two primary divisions:

- Raw peat soils
- Earthy peat soils

The latter group being characterised by a ripening of the topsoil, whilst raw peat soils are characterised by a lack of an earthy top soil.
At soil subgroup level classification is dependent upon the degree of decomposition and pH of the organic horizons of the reference profile, extending from 30 – 90 cm below the surface (assuming the lower boundary of the organic layer is deeper than 90 cm).

1. Raw peat soils:
    - Raw oligo-fibrous peat soils
    - Raw eu-fibrous peat soils
    - Raw oligo-amorphous peat soils
    - Raw eutro-amorphous peat soils

2. Earthy peat soils:
    - Earthy oligo-fibrous peat soils
    - Earthy eu-fibrous peat soils
    - Earthy oligo-amorphous peat soils
    - Earthy eutro-amorphous peat soils
    - Earthy sulfuric peat soils

In classifying soil series, the determining factor is the nature of the parent material. In peat soils such classification is made according to the botanical properties of the parent material. However, it is also partially based on the presence of contrasting materials or distinctive mineralogies (Burton and Hodgson, 1987). Table 16 lists soil series as they currently stand.

Subgroup Code	Soil Series	Subgroup Code	Modern definition#
10.11	Floriston	fL	Grass-sedge peat
10.11	Longmoss	LN	Sphagnum peat
10.11	Winter Hill	WH	Mixed Eriophorum and Sphagnum peat
10.12	Ousby	Ou	Grass-sedge peat
10.13	Crowdy	CJ	Humified peat
10.13	Hepste	Hps	Humified peat over litho-skeletal material
10.21	Ridley	rL	Grass-sedge peat
10.21	Turbary Moor	M	Mixed Eriophorum and Sphagnum peat
10.21	Westhay	wJ	Sphagnum peat
10.22	Acre	AC	Grass-sedge peat with mineral layers
10.22	Altcar	Aq	Grass-sedge peat
10.23	Blackland	BL	Humified peat
10.24	Adventurers'	An	Humified peat
10.24	Bottisham	bO	Humified loamy peat
10.24	Martin Mere	Mh	Sedimentary peat
10.25	Mendham	mP	Sulfuric-humified peat
10.25	Prickwillow	Pw	Sulfuric-humified peat with mineral layers

Table 16: Peat soil series in England and Wales.

Each organic horizon in the reference horizon being assigned to one of the six types of organic material.

Degree of decomposition	Nature of liquid expressed on squeezing	Proportion of peat extruded between fingers	Nature of residue	Description
H1	Clear, colourless	None	Plant structure unaltered; fibrous, elastic	Undecomposed
H2	Almost clear, yellow-brown	None	Plant structure distinct; almost unaltered	Almost undecomposed
H3	Slightly turbid, Brown	None	Plant structure distinct; most remains easily identifiable	Very weakly decomposed
H4	Strongly turbid Brown	None	Plant structure distinct; most remains identifiable	Weakly decomposed
H5	Contains a little peat in suspension	Very little	Plant structure clear but becoming indistinct; most remains difficult to identify	Moderately decomposed
H6	'muddy'# much peat in suspension	One-third	Plant structure indistinct but clearer in the squeezed residue than in undisturbed peat; most remains identifiable	Well decomposed
H7	Strongly 'muddy'	One-half	Plant structure indistinct but recognisable; few remains identifiable	Strongly decomposed
H8	Thick 'mud' little free water	Two-thirds	Plant structure indistinct; only resistant remains such as root fibres and wood identifiable	Very strongly decomposed
H9	No free water	Nearly all	Plant structure almost unrecognisable; practically no identifiable remains	Almost completely decomposed
H10	No free water	All	Plant structure unrecognisable; completely amorphous	Completely decomposed

Table 17: von Post scale (after Burton and Hodgson, 1987).

muddy does not refer to mineral content, but to the appearance and consistency of the expressed liquid.

C Methods for physical and hydraulic peat soil property analysis.

C.1 Organic matter determination by muffle furnace (loss-on-ignition).

Method

1. Sieve the soil sample on a 2 mm sieve, and crushed retained particles other then stones to pass 2 mm sieve.

2. Dry the prepared soil over night in the oven at temperature of 50 (+/-1.5 $^{\circ}$C).

3. Weigh the dry silica dish to the nearest 0.0001g (m_d).

4. Place 5.00 g of the soil on the silica dish (m_1) and place the dish in the unheated furnace, heat to 440 (+/-25 $^{\circ}$C), and maintain this temperature for a period of not less than 3 hours, or until constant mass is achieved.

5. Remove silica dish and contents from the furnace and allow to cool to room temperature in the dessicator.

6. Weigh the dish and contents to the nearest 0.0001 g (m_2).

Calculation

Calculate the mass loss-on-ignition as a percentage of the dry mass of soil passing a 2 mm sieve from the equation:

$$\mathrm{SOM}(\%) = \left(\frac{M_1 - M_2}{M_1 - M_d}\right) \times 100$$

Equation 35: Soil organic matter content.

where SOM is reported as a percentage. M_1 is the mass of the silica dish and oven dry soil in g, M_2 is the mass of dish and soil after combustion in g and M_d is the mass of silica dish in g.

C.2 Organic carbon determination by CNS analyser (VARIO EL)

General measuring principle

The elementary analyser Vario EL is fully automatic instrument for the quantitative determination of Carbon, Nitrogen and Sulphur.
The elementary analyser Vario EL works according to the principle of catalytic tube combustion in an oxygenated CO_2 atmosphere and high temperatures. The combustion gases are freed from foreign gases (for instance volatile halogen). The desired measuring components are separated from each other with the help of specific adsorption columns and determined in succession with a thermal conductivity detector (TCD). Helium (He) serves as flushing and carrier gas.
The automatic control of the analysis procedure is accomplished through the software.

Sample loading

The homogenized sample is packed in tin foil, weighed and placed into the carousel of the automatic sample feeder. The sample name and the matrix specific oxygen dosing are allocated to the sample weight.
At the start of an analysis, the "auto-zero adjust" of the measuring signal is carried out through the detector. Thereafter the ball valve opens through a 180º turn of the blind hole ball. The carousel moves up one position and the sample drops into the ball valve. The ball valve turns 90º into flushing position and seals the apparatus. The atmospheric nitrogen that had entered is flushed out and the sample drops into the ash finger of the combustion tube through another 90 turn of the ball valve.

Sample digestion and removal of foreign gases (cn-mode)

Parallel to the sample feeding procedure, the oxygen dosing in the ash finger begins, so that the sample drops into a highly oxygenated atmosphere and combusts explosively. During oxidised combustion the elements C and N produce, in addition to the molecular nitrogen (N_2), the oxidation products CO_2, NOX.
A copper oxide filling inside the combustion tube works as catalyst for quantitative oxidation of higher carbon oxide and samples that are difficult to combust.
Volatile Fluor compounds are chemically bound on a layer of ceroxide and the lead chromate filling absorbs the sulphur compounds (SO_2 / SO_3).

A copper filling in the reduction tube quantitatively reduces nitrogen oxides (NOX) to N_2 and binds excess oxygen.

The volatile halogen compounds are removed from the gas stream at the exit of the reduction tube with silver wool. The remaining gas stream contains only CO_2, H_2O and N_2 in the carrier gas (He).

In the CN- Mode the gas stream is freed of H_2O with a built in absorption U-tube and guided to a modified separation system.

Separation of the measuring components (CN-mode)

The separation of measuring components is carried out through specific adsorption on heatable columns. In each mode of operation only the necessary adsorption columns are built into the gas path. This column adsorbs the CO_2 and the measuring gas stream contains only N_2, which is measured directly in the thermal conductivity detector (TCD). After the N-measurement, the CO_2 is likewise thermally desorbed and measured. When the integration of a component is concluded, the integral value is stored, an integrator reset is carried out and the next component is desorbed by the adsorption column and measured.

Detection

The thermal conductivity detector consists of two measuring chambers. The gas flows through them at constant rate of flow. During measuring operation the reference measuring chamber is flushed with pure carrier gas He while the measuring gas flow, i.e. the respectively desorbed fraction of the reaction gas (e.g. He/N_2 – or He/CO_2 – mixture) passes through the other one. The detector output voltage is recorded as a function of time and digitized.

Through the calibration for each element the integral is allocated to an absolute element content of the sample. From the resulting content and the sample weight, the percentage of the element content is calculated.

C.3 Particle Density (Pycnometer Method)

Method

1. Weigh a clean dry pycnometer in air.
2. Add 10 g of air dry soil sieved through a 2 mm sieve.
3. Weigh pycnometer, stopper and contents.
4. Determine moisture content of a duplicate soil sample by drying at 105 ºC.
5. Fill pycnometer half full with hexane (non polar fluid) to wash soil adhering to side of neck.
6. Gently boil for several minutes to remove any trapped air.
7. Cool pycnometer to room temperature.
8. Add enough hexane to fill pycnometer to neck and insert stopper.
9. Clean and dry the outside of the pycnometer.
10. Weigh pycnometer and contents.
11. Remove soil and re-clean pycnometer.
12. Fully refill pycnometer with hexane only, insert stopper, thoroughly dry and weigh.

Calculation of particle density:

$$\rho_{pd} = \frac{\rho_w \left(W_s - W_a\right)}{\left[\left(W_s - W_a\right) - \left(W_{sw} - W_w\right)\right]}$$

Equation 36: Particle density equation.

where W_s is the weight of pycnometer plus soil sample corrected to oven dried water content; W_a is the weight of pycnometer filled with air; W_{sh} is the weight of pycnometer filled with soil and hexane; and, W_h = weight of pycnometer filled with water at room temperature.

C.4 Water release characteristics

Sand-table

1. Level off without smearing one surface of the undisturbed soil sample and cover with a taut piece of wetted nylon. The nylon should be clipped to the sampling cylinder using an elastic band so that there are no wrinkles, thus giving good contact between the soil and the nylon.
2. The soil samples are placed on a shallow plastic tray and water is added to within 10 mm of the top of the samples. They are then allowed to saturate for 48 hours.
3. Press the sampling cylinder into the surface of the sand-table to achieve good contact between the sample and the sand. The sand-table must be tightly covered to prevent evaporation.

4. The first suction is then applied to the soil sample, measuring from the sand surface.
5. At equilibrium, one week later, remove samples, dry the outside, weigh, and record weight at that particular suction.
6. Replace samples as before and adjust manometer to appropriate suction. Leave until equilibrium is established and weigh again.

Pressure Membrane

1. Saturate the undisturbed soil sample and soak the cellulose membrane in water overnight. Prepare two soil samples and ensure no stones or flints protrude on the base of the sample before saturation.
2. Cut the membrane to size on the jig provided and check to ensure it is free from holes.
3. Carefully clean the base of the pressure cylinder, for any traces of grit will damage the membrane.
4. Place the membrane on the sintered base plate of the pressure cylinder and lay the soil carefully on top of the membrane. Place the O-ring seal and collar on top of the base ensuring there is no grit or soil between the O-ring and the membrane.
5. Bolt down the top plate using a torque of 15 ft lb (20.4 N-m).
6. Weigh the collecting bottle containing a little oil (used to prevent water evaporation) and then attach to the pressure cylinder.
7. Apply the required pressure to the soil, opening the valves slowly (particularly those connected to the more sensitive gauges) and make any pressure adjustments with everything sealed. Close regulating valve so that if there are any leaks in the system, the nitrogen cylinder is not completely emptied.
8. Check for any gas leaks and never blow off the relief valve. (Blow off pressure 1580 kPa [230 psi]).
9. Leave the apparatus for two weeks, but observe at regular intervals to ensure there are no leaks and the required pressure is maintained. At the end of the two-week period re-weigh the collecting bottle.
10. Replace the collecting bottle and increase the pressure. This may mean re-positioning the apparatus on the table. Leave for two weeks. Repeat this procedure for the pressures required.

11. After the final weighing (after two weeks at -150 m pressure potential), dismantle the apparatus and determine the total weight of the soil left and its water content.
12. Calculate the water content of the soil at the other pressures.
13. Use pressures of 10, 20, 40, 80 and 150 m pressure potential.
14. Plot the results on the soil water characteristic curve of the soil.
15. After equilibrium has been established at the final suction, weigh and dry complete sample in oven. Calculate soil water content at final suction.
16. Using values of weight of oven dry soil and weights of sampling cylinder, metal clip and nylon, calculate water content at other suction values.

C.5 Saturated Hydraulic Conductivity determination by Falling Head Permeameter

Method

1. The bevelled cutting edge on the body of the falling head permeameter facilitates collection of minimally disturbed peat samples.
2. The sample is slowly saturated with water from the base upwards to remove air pockets in the soil
3. A record is made of the head of water in the manometer tube.
4. The tap on the line connecting the apparatus to the constant head feed is closed. (As soon as the tap is closed the level of water in the manometer starts to fall).
5. The time taken for the level to drop by about 0.2 m is measured or the the change in manometer water level over a fixed interval of time is recorded (dependent on peat permeability).
6. The measurement is repeated using a lower initial head.
7. Note: given the soil is saturated, the inflow from the manometer will be equal to the flow through the soil sample.

Calculations

If the water level in the manometer falls Δh in time Δt the volume of water lost from the standpipe in unit time is Q:

$$Q = -a\frac{\Delta h}{\Delta t}$$

Equation 37: Falling head permeameter determination of Ksat.

Integrating between the limits $h = h_1$ at $t = t_1$ and $h = h_2$ at $t = t_2$

$$-a\int_{h_1}^{h_2}\frac{1}{h}\Delta h = \frac{KA}{L}\int_{t_1}^{t_2} t\Delta t$$

Equation 38: Integration of saturated hydraulic conductivity data

i.e. $a.\ln(h_1/h_2) = (KA)/L(t_2 - t_1)$ and $K = \{(a.L)/[A(t_2 - t_1)]\} \times 1n(h_1/h_2)$.

Note: units of are reported in m s^{-1} as L is in metres and time (t) is in seconds.

C.6 Field Measurement of saturated hydraulic conductivity

Method

1. A borehole is augered into the soil to 2.0 m depth below the water table.
2. When the water level in the borehole reaches equilibrium with the surrounding ground-water, part of the water is removed.
3. The rate at which the water rises in the borehole is measured and the first 25 per cent of recharge is used to calculate hydraulic conductivity (K), according to **Error! Reference source not found.**.
4. In total five readings are taken during each test.

5. The following assumptions were made:
6. the water table was not lowered around the hole when the water is removed,
7. the water flowed horizontally into the hole from the sides and vertically up through the bottom of the borehole.

Calculations

$$K = C\frac{\Delta Y}{\Delta t}$$

Equation 39: Calculation of hydraulic conductivity by auger hole method

where C is function of Y, H, r and S. Δt is the difference in time between recorded observations. ΔY is the head change between the predefined time intervals.

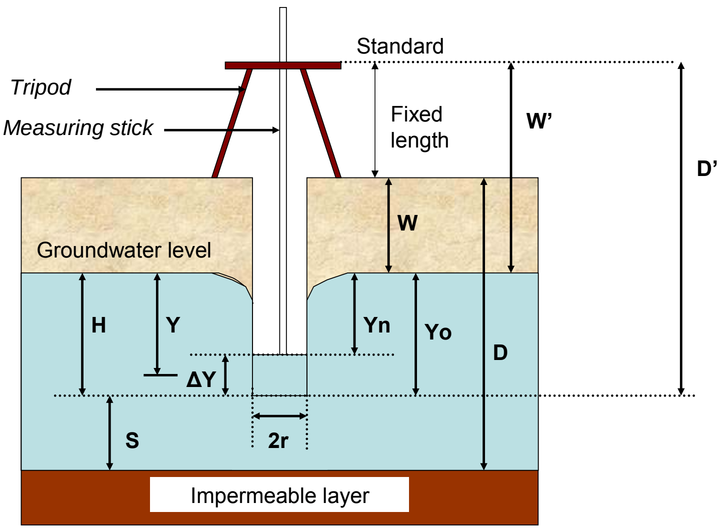

Figure 64: Schematic of auger hole parameters required to determine K

where:

- All reading are taken from reference point: 'A'
- The depth of the hole, from reference point is D'
- The depth of the hole from soil surface is D
- The depth of groundwater level from reference point is W'
- The depth of groundwater from soil surface is W
- The depth of hole from groundwater level is H
- The radius of the hole is r
- The depth from base of hole to the impermeable layer is S

D Tables of data from topographic and soil survey analyses.

D.1 Topographical survey data

Field Number	1993	2003	Change in elevation		
1/2	4.95	4.99	0.47		
3	4.92	5.04	1.15		
4	4.96	5.06	0.97		
5	4.88	5.01	1.25		
6	4.92	5.10	1.79		
7	5.01	5.15	1.45		
8	4.95	4.99	0.37		
9	4.93	5.01	0.79		
10	4.86	4.90	0.32		
11	4.91	5.09	1.80		
12	4.91	5.01	1.00		
13	4.93	4.98	0.50		
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Year	1	0.30	0.30	12.37	<.001
Residual	94	2.30	0.02		
Total	95	2.60			
		LSD: 0.06			

Table 18: Long-term change in surface elevation and ANOVA of long-term change in surface elevation at West Sedgemoor.

Field	Summer 2003	Winter 2003	Winter 2004	Annual Change	Seasonal Change
1	**4.83**	**4.89**	**4.87**	-0.01	0.05
2	**4.85**	**4.92**	**4.90**	-0.01	0.06
3	**4.83**	**4.90**	**4.87**	-0.02	0.07
4	**4.87**	**4.94**	**4.88**	-0.05	0.06
5	**4.80**	**4.93**	**4.90**	-0.02	0.12
6	**4.86**	**4.98**	**4.93**	-0.04	0.12
7	**4.93**	**4.93**	**5.03**	0.11	0.00
8	**4.87**	**4.90**	**4.89**	0.00	0.03
9	**4.86**	**4.87**	**4.88**	0.01	0.01
10	**4.87**	**4.91**	**4.92**	0.01	0.04
11	**4.91**	**4.89**	**4.90**	0.02	-0.03
12	**4.86**	**4.87**	**4.88**	0.01	0.01
13	**4.90**	**4.93**	**4.93**	0.00	0.02

Table 19: Mean surface elevation of prescribed points at West Sedgemoor.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Year	1	0.000246	0.000246	0.18	0.676
Residual	24	0.032938	0.001372		
Total	25	0.033185			
LSD: 0.03					

Table 20: ANOVA of annual change in surface elevation at West Sedgemoor.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Season	1	0.015	0.015	13.780	0.001
Residual	24	0.026	0.001		
Total	25	0.041			
LSD: 0.03					

Table 21: ANOVA of seasonal change in surface elevation at West Sedgemoor.

D.2 Peat thickness

Grand Mean (all peats)	Fen Clay	Fibrous	Humified
1.59	1.70	2.07	1.02
LSD: 0.53			

Table 22: Fall in surface elevation over 13 year period according to areas where different peat types predominate at Methwold Fen.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Peat type	2	22.19	11.09	7.91	<.001
Residual	114	159.91	1.40		
Total	116	182.10			
LSD: 0.53cm					

Table 23: ANOVA of fall in surface elevation of areas where different peat types predominate at Methwold Fen

D.3 Soil pH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Point location	12	17.30	1.44	9.08	<.001
Depth	2	5.11	2.55	16.10	<.001
Time	1	1.03	1.03	6.51	0.013
Residual	62	9.84	0.16		
Total	77	33.28			
LSDs: point locations 0.46; Depth 0.22 and time of analysis 0.18					

Table 24: West Sedgemoor ANOVA of soil pH.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Point location	21	145.48	6.93	27.43	<.001
Depth	2	32.78	16.39	64.91	<.001
Time	3	0.99	0.33	1.3	0.275
LSDs: point locations 0.31; Depth 0.15 and time of analysis 0.13					

Table 25: Methwold Fen ANOVA of soil pH.

E Tables of data for physical and hydraulic parameters

E.1 Organic matter content

Horizon	Soil type	averages	n	S.D.	SE	95% CI
A	Peaty Loam	38.99	12	7.3	2.1	4.6
B	Humified	60.09	12	3.8	1.1	2.4
C	Semi-fibrous	69.26	12	2.6	0.8	1.7
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Soil type	2.00	6985.56	3492.78	139.68	<.001	
Residual	32.00	800.17	25.01			
Total	34.00	7766.92				
LSD for soil type = 4.16						

Table 26: West Sedgemoor Organic Matter content (g g^{-1}) of different peats and ANOVA of SOM.

Horizon	Soil type	averages	n	S.D.	SE	95%CI
A/B	Amorphous	67.32	9	9.8	3.0	6.8
C	Semi-fibrous	80.06	9	9.5	2.9	6.6
D	Fibrous	80.48	9	6.3	1.9	4.4
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Soil_type	3	1346.21	448.74	5.79	0.003	
Residual	32	2479.89	77.5			
Total	35	3826.1				
LSD for soil type = 8.45						

Table 27: Methwold Fen Soil Organic Matter content (g g^{-1}) of different peats and ANOVA of SOM.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	497.14	497.14	10.31	0.003
Soil_Type	1	1071.91	1071.91	22.23	<.001
Location.Soil_Type	1	0.67	0.67	0.01	0.907
Residual	32	1543.21	48.23		
Total	35	3112.93			
LSD of location and soil type = 4.72 and location*soil type= 6.67					

Table 28: ANOVA of SOM for common peats of West Sedgemoor and Methwold Fen peats (Humified and Semi-fibrous).

E.2 Organic Carbon content

Horizon	Soil type	averages	n	S.D.	SE	95% CI
A	Peaty Loam	21.30	12	4.0	1.2	2.6
B	Humified	37.70	12	6.7	2.0	4.4
C	Semi-fibrous	43.81	12	1.6	0.5	1.1
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Soil_type	2	1976.44	988.22	93.95	<.001	
Residual	15	157.77	10.52			
Total	17	2134.21				
LSD: 3.99						

Table 29: West Sedgemoor soil organic carbon content (%) and ANOVA of SOC content for different peats.

Horizon	Soil type	averages	n	S.D.	SE	95%CI
A/B	Amorphous	38.03	9	5.5	1.7	3.8
C	Semi-fibrous	44.48	9	5.3	1.6	3.7
D	Fibrous	47.07	9	3.7	1.1	2.6
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Soil_type	2	355.09	177.54	6.36	0.01	
Residual	15	418.82	27.92			
Total	17	773.91				
LSD: 6.5						

Table 30: Methwold Fen soil organic carbon content (%) and ANOVA of SOC content for different peats.

E.3 SOM conversion factors

Horizon	Soil type	Average	n	SD	SE	95% CI
A	Peaty Loam	1.83	9	0.239397	0.079799	0.184016
B	Humified	1.73	9	0.322046	0.107349	0.247546
C	Semi-fibrous	1.65	9	0.026727	0.008909	0.020544
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Soil_Type	2	0.15576	0.07788	1.44	0.257	
Residual	24	1.29771	0.05407			
Total	26	1.45347				
LSD: 0.226						

Table 31: West Sedgemoor peat conversion factors and ANOVA of conversion factors for different peat soils.

Horizon	Soil type	Average	n	SD	SE	95% CI
A/B	Amorphous	1.77	9	0.067451	0.022484	0.051847
C	Semi-fibrous	1.80	9	0.069019	0.023006	0.053053
D	Fibrous	1.71	9	0.080981	0.026994	0.062247

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_Type	2	0.057985	0.028993	5.41	0.011
Residual	24	0.128578	0.005357		
Total	26	0.186563			

LSD: 0.07

Table 32: Methwold Fen peat conversion factors and ANOVA of conversion factors for different peat soils.

E.4 Soil Ash content

Horizon	soil type	averages	n	S.D.	SE	95% CI
A	Peaty Loam	61.01	12	7.3	2.2	4.8
B	Humified	34.78	12	11.5	3.5	7.7
C	Semi-fibrous	27.71	12	2.6	0.8	1.7

Table 33: West Sedgemoor Ash Content (g g^{-1})

Horizon	Soil type	averages	n	S.D.	SE	95%CI
A/B	Amorphous/Humified	32.68	9	9.8	3.5	8.0
C	Semi-fibrous	19.94	9	9.5	3.4	7.8
D	Fibrous	19.52	9	6.3	2.2	5.1

Table 34: Methwold Fen Ash Content (g g^{-1})

E.5 Particle Density

Horizon	Soil type	Average	n	SD	SE	95%CI
A	Peaty Loam	1.57	5	0.2	0.1	0.2
B	Humified	1.33	5	0.1	0.1	0.2
C	Semi-fibrous	1.24	5	0.1	0.1	0.2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_Type	2	0.29865	0.14933	6.12	0.015
Residual	12	0.29264	0.02439		
Total	14	0.59129			

LSD soil type = 0.2152

Table 35: West Sedgemoor particle Density (g cm^{-3}) and ANOVA of particle density.

Horizon	Soil type	Average	n	SD	SE	95%CI
A/B	Amorphous	1.37	3	0.1	0.0	0.2
C	Semi-fibrous	1.19	3	0.3	0.2	0.8
D	Fibrous	1.10	3	0.1	0.0	0.2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_Type	2	0.11236	0.05618	1.45	0.307
Residual	6	0.233	0.03883		
Total	8	0.34536			

LSd soil type = 0.394

Table 36: Methwold Fen particle density (g cm^{-3}) and ANOVA of particle density.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	0.00963	0.00963	0.27	0.616
Soil_Type	1	0.08333	0.08333	2.35	0.164
Location.Soil_Type	1	0.0012	0.0012	0.03	0.859
Residual	8	0.2838	0.03547		
Total	11	0.37797			

LSD of soil type and location = 0.251 and of soil type*location = 0.355

Table 37: ANOVA for particle density for common soils from West Sedgemoor and Methwold Fen (Humified and Semi-fibrous peats)

E.6 Dry Bulk Density

Horizon	Soil Type	Averages	n	SD	SE	95% CI
A	Peaty Loam	0.44	6	0.1	0.0	0.06
B	Humified	0.17	6	0.0	0.0	0.03
C	Semi-fibrous	0.09	6	0.0	0.0	0.00

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_Type	2	0.40	0.20	120.74	<.001
Residual	15	0.02	0.00		
Total	17	0.42			

LSD of soil type = 0.050

Table 38: West Sedgemoor Dry Bulk Density (g cm^{-3}) and ANOVA of dry bulk density.

Horizon	Soil Type	Averages	n	SD	SE	95% CI
A/B	Amorphous	0.35	6	0.0	0.0	0.01
C	Semi-fibrous	0.15	6	0.0	0.0	0.01
D	Fibrous	0.12	6	0.0	0.0	0.02

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_Type	2	0.19	0.09	439.69	<.001
Residual	15	0.00	0.00		
Total	17	0.19			

LSD of soil type = 0.018

Table 39: Methwold Fen Dry Bulk Density (g cm^{-3}) and ANOVA of dry bulk density.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	0.077067	0.077067	261.24	<.001
Soil_Type	1	0.114817	0.114817	389.21	<.001
Location.Soil_Type	1	0.022817	0.022817	77.34	<.001
Residual	20	0.01	0.000295		
Total	23	0.22			
LSD of soil type and location = 0.015 and Soil type*location = 0.021					

Table 40: ANOVA of dry bulk density for peat soils common to both West Sedgemoor and Methwold Fen.

E.7 Maximum Porosity

Horizon	Soil Type	Average	n	SD	SE	95%CI
A	Peaty Loam	0.719	6	0.041	0.018	0.047
B	Humified	0.872	6	0.023	0.010	0.026
C	Semi-fibrous	0.924	6	0.004	0.002	0.004
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Soil_type	2	0.13	0.07	90.02	<.001	
Residual	15	0.01	0.00			
Total	17	0.15				
LSD of soil type = 0.034						

Table 41: West Sedgemoor maximum porosity (cm^3 cm^{-3}) and ANOVA of maximum porosity.

Horizon	Soil Type	Average	n	SD	SE	95%CI
A/B	Amorphous	0.802	6	0.023	0.010	0.027
C	Semi-fibrous	0.871	6	0.014	0.006	0.017
D	Fibrous	0.858	6	0.010	0.004	0.011
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Soil_type	2	0.02	0.01	24.81	<.001	
Residual	15	0.01	0.00			
Total	17	0.02				
LSD of soil type = 0.023						

Table 42: Methwold Fen maximum porosity (cm^3 cm^{-3}) and ANOVA of maximum porosity.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	0.0222042	0.022204	60.97	<.001
Soil_type	1	0.0222042	0.022204	60.97	<.001
Location.Soil_type	1	0.0005042	0.000504	1.38	0.253
Residual	20	0.0072833	0.000364		
Total	23	0.0521958			
LSD of soil type and location = 0.016 and soil type*location = 0.023					

Table 43: ANOVA of maximum porosity for peats common to West Sedgemoor and Methwold Fen (Humified and Semi-fibrous peats).

Parameter	estimate	s.e.	t(34)	t pr.
Constant	0.6328	0.03	19.88	<.001
Organic_Matter	0.32	0.05	6.71	<.001
percentage variance accounted for 55.7				

Table 44: Regression analysis of SOM content effect on maximum porosity.

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.126	0.126	108.07	<.001
Residual	34	0.040	0.001		
Total	35	0.166	0.005		
Percentage variance accounted for 75.4					

Table 45: Linear regression analysis of the effect of dry bulk density on maximum porosity.

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	2	0.128	0.064	54.5	<.001
Residual	33	0.039	0.001		
Total	35	0.166	0.005		
Percentage variance accounted for 75.4					

Table 46: Multiple regression analysis of combined effects of SOM content and bulk density on maximum porosity.

E.8 Void ratio

Horizon	Soil type	Average	n	SD	SE	95%CI
A	Peaty Loam	2.63	6	0.5	0.2	0.6
B	Humified	6.99	6	1.4	0.6	1.6
C	Semi-fibrous	12.11	6	0.6	0.3	0.7

Table 47: West Sedgemoor void ratios.

Horizon	Soil type	Average	n	SD	SE	95%CI
A/B	Amorphous	4.11	6	0.6	0.3	0.7
C	Semi-fibrous	6.81	6	0.9	0.4	1.1
D	Fibrous	6.05	6	0.5	0.2	0.6

Table 48: Methwold Fen void ratios

E.9 Shrinkage

Empirical shrinkage

Horizon	Soil type	volume loss (%)	n	SE	95%CI
A	Amorphous	37.20	4	1.2	3.8
B	Semi-fibrous	61.59	4	3.2	10.0
D	Fibrous	73.67	4	3.4	10.8

Table 49: Loss in volume between 'Fresh' and oven dried peat states for a range of soils from Methwold Fen.

Shrinkage Characteristics

Soil type	Tension (Bar)	Moisture Ratio	n	SD	95%CI	Void Ratio	n	SD	95% CI
Amorphous	0	4.60	3	1.28	3.17	4.60	3	1.28	3.17
Amorphous	0.02	4.01	3	1.07	2.65	4.59	3	1.29	3.22
Amorphous	0.04	3.63	3	0.97	2.42	4.53	3	1.40	3.49
Amorphous	0.06	3.41	3	0.91	2.25	4.31	3	1.35	3.35
Amorphous	0.08	3.29	3	0.87	2.17	4.31	3	1.35	3.35
Amorphous	0.1	3.18	3	0.84	2.10	4.43	3	1.36	3.37
Amorphous	1	2.72	3	0.86	2.13	4.18	3	1.36	3.37
Amorphous	2	2.64	3	0.80	1.99	4.10	3	1.28	3.18
Amorphous	4	2.59	3	0.79	1.95	4.04	3	1.29	3.20
Amorphous	8	2.49	3	0.7	1.752	3.84	3	1.18	2.93
Amorphous	10	2.31	3	0.7	1.78	3.69	3	1.06	2.63
Amorphous	15	2.28	3	0.7	1.758	3.57	3	1.07	2.65
Amorphous	OVEN	0.00	3	0	0	2.35	3	0.91	2.26
Semi-fibrous	0	8.59	3	1.9	4.771	8.59	3	1.92	4.77
Semi-fibrous	0.02	7.83	3	1.8	4.497	8.62	3	1.86	4.61
Semi-fibrous	0.04	7.28	3	1.8	4.37	8.62	3	1.86	4.61
Semi-fibrous	0.06	6.93	3	1.7	4.26	8.35	3	1.90	4.72
Semi-fibrous	0.08	6.70	3	1.7	4.173	8.35	3	1.90	4.72
Semi-fibrous	0.1	6.44	3	1.6	4.065	8.45	3	1.97	4.89
Semi-fibrous	1	6.16	3	0.7	1.795	7.81	3	1.81	4.51
Semi-fibrous	2	4.69	3	0.7	1.649	7.63	3	1.64	4.08
Semi-fibrous	4	4.49	3	0.6	1.373	7.44	3	1.73	4.30
Semi-fibrous	8	4.32	3	0.5	1.187	7.08	3	1.71	4.25
Semi-fibrous	10	4.15	3	0.4	1.07	6.95	3	1.50	3.72
Semi-fibrous	15	4.09	3	0.4	1.057	6.72	3	1.45	3.61
Semi-fibrous	OVEN	0.00	3	0	0	4.46	3	1.06	2.63
Fibrous	0	6.97	3	2.6	6.356	6.97	3	2.56	6.36
Fibrous	0.02	6.03	3	2.6	6.556	7.16	3	2.55	6.34
Fibrous	0.04	5.77	3	2.6	6.515	7.16	3	2.55	6.34
Fibrous	0.06	5.53	3	2.6	6.411	6.89	3	2.33	5.79
Fibrous	0.08	5.36	3	2.5	6.299	6.89	3	2.33	5.79
Fibrous	0.1	5.17	3	2.5	6.138	6.97	3	2.56	6.36
Fibrous	1	4.53	3	1.2	3.063	6.16	3	2.50	6.22
Fibrous	2	3.76	3	0.9	2.299	5.28	3	2.07	5.14
Fibrous	4	3.55	3	0.9	2.139	5.08	3	1.99	4.94
Fibrous	8	3.36	3	0.8	2.032	4.78	3	2.00	4.97
Fibrous	10	3.21	3	0.9	2.244	4.74	3	1.99	4.94
Fibrous	15	3.09	3	0.8	2.024	4.51	3	1.81	4.50
Fibrous	OVEN	0.00	3	0	0	3.44	3	1.55	3.84

Table 50: Shrinkage Characteristics data for Methwold Fen peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	249.82	124.91	39.11	<.001
Tension	12	106.59	8.88	2.78	0.003
Soil_type.Tension	24	13.13	0.55	0.17	1
Residual	78	249.13	3.19		
Total	116	618.67			
LSDs: Soil type = 0.806, Tension = 1.68 and Soil type*Tension = 2.91					

Table 51: ANOVA of void ratio for Methwold Fen peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	138.14	69.07	36.04	<.001
Tension	12	314.59	26.22	13.68	<.001
Soil_type.Tension	24	25.52	1.06	0.55	0.948
Residual	78	149.50	1.92		
Total	116	627.75			
LSDs: Soil type = 0.624, Tension = 1.30 and Soil type*Tension = 2.25					

Table 52: ANOVA of moisture ratio for Methwold Fen peats.

Soil type	Tension (Bar)	Moisture Ratio	n	SD	95%CI	Void Ratio	n	SD	95% CI
Peaty Loam	0	6.23	3	0.79	1.97	6.23	3	0.79	1.97
Peaty Loam	0.02	5.82	3	0.83	2.06	6.23	3	0.79	1.97
Peaty Loam	0.04	5.72	3	0.86	2.14	6.05	3	0.72	1.80
Peaty Loam	0.06	5.64	3	0.90	2.23	6.05	3	0.72	1.80
Peaty Loam	0.08	5.57	3	0.92	2.28	6.18	3	0.87	2.17
Peaty Loam	0.1	5.51	3	0.94	2.33	5.80	3	1.13	2.80
Peaty Loam	1	4.66	3	1.06	2.64	5.89	3	1.01	2.51
Peaty Loam	2	4.30	3	0.98	2.43	5.89	3	1.01	2.51
Peaty Loam	4	4.09	3	0.91	2.27	5.68	3	1.08	2.68
Peaty Loam	8	3.52	3	0.89	2.20	5.47	3	1.22	3.04
Peaty Loam	10	3.53	3	0.91	2.25	5.35	3	1.19	2.95
Peaty Loam	15	3.46	3	0.97	2.40	5.26	3	1.11	2.76
Peaty Loam	OVEN	0.00	3	0.00	0.00	5.03	3	0.96	2.38
Humified	0	10.40	3	3.60	8.95	10.40	3	3.60	8.95
Humified	0.02	9.62	3	3.09	7.68	10.40	3	3.60	8.95
Humified	0.04	9.26	3	2.89	7.18	10.11	3	3.84	9.55
Humified	0.06	9.01	3	2.83	7.02	10.11	3	3.84	9.55
Humified	0.08	8.82	3	2.77	6.87	10.11	3	3.84	9.55
Humified	0.1	8.61	3	2.71	6.74	10.05	3	3.91	9.72
Humified	1	8.34	3	4.02	9.98	8.66	3	3.44	8.54
Humified	2	6.17	3	1.85	4.59	7.91	3	3.38	8.41
Humified	4	5.74	3	1.67	4.16	7.61	3	3.42	8.49
Humified	8	5.47	3	1.58	3.92	7.35	3	3.68	9.13
Humified	10	5.14	3	1.32	3.29	7.11	3	3.86	9.59
Humified	15	5.03	3	1.54	3.82	6.81	3	3.46	8.59
Humified	OVEN	0.00	3	0.00	0.00	4.74	3	2.62	6.52
Semi-fibrous	0	7.31	3	0.82	2.03	7.31	3	0.82	2.03
Semi-fibrous	0.02	6.46	3	0.68	1.70	7.31	3	0.82	2.03

Semi-fibrous	0.04	6.13	3	0.63	1.57	6.96	3	0.78	1.94
Semi-fibrous	0.06	5.73	3	0.53	1.32	6.27	3	1.02	2.54
Semi-fibrous	0.08	5.46	3	0.53	1.31	6.27	3	1.02	2.54
Semi-fibrous	0.1	5.15	3	0.47	1.17	6.27	3	1.02	2.54
Semi-fibrous	1	4.46	3	0.33	0.81	5.71	3	0.31	0.77
Semi-fibrous	2	3.70	3	0.44	1.10	5.28	3	0.08	0.19
Semi-fibrous	4	3.36	3	0.45	1.11	4.95	3	0.38	0.95
Semi-fibrous	8	3.30	3	0.14	0.35	4.73	3	0.21	0.53
Semi-fibrous	10	3.13	3	0.07	0.18	4.57	3	0.39	0.97
Semi-fibrous	15	2.90	3	0.18	0.44	4.52	3	0.32	0.79
Semi-fibrous	OVEN	0.00	3	0.00	0.00	2.57	3	0.28	0.69

Table 53: Shrinkage Characteristics data for West Sedgemoor peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	216.38	108.19	22.65	<.001
Tension_M	12	146.82	12.24	2.56	0.007
Soil_type.Tension_M	24	40.20	1.68	0.35	0.997
Residual	78	372.59	4.78		
Total	116	775.99			

LSDs: Soil type = 0.985, Tension = 2.05 and Soil type*Tension = 3.55

Table 54:ANOVA of void ratio on West Sedgemoor peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	178.62	89.31	36.4	<.001
Tension_M	12	490.84	40.90	16.67	<.001
Soil_type.Tension_M	24	32.89	1.37	0.56	0.946
Residual	78	191.39	2.45		
Total	116	893.74			

LSDs: Soil type = 0.706, Tension = 1.47 and Soil Type* Tension = 2.55

Table 55: ANOVA of moisture ratio on West Sedgemoor peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	60.838	60.84	13.57	<.001
Soil_type	1	3.601	3.60	0.80	0.372
Tension	12	211.974	17.67	3.94	<.001
Location.Soil_type	1	418.398	418.40	93.33	<.001
Location.Tension	12	20.221	1.69	0.38	0.969
Soil_type.Tension	12	1.049	0.09	0.02	1.00
Location.Soil_type.Tension	12	10.437	0.87	0.19	0.998
Residual	104	466.255	4.48		
Total	155	1192.772			

Table 56: ANOVA of void ratio for similar soils from West Sedgemoor and Methwold Fen (Humified and Semi-fibrous peats).

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	91.663	91.66	41.25	<.001
Soil_type	1	0.000	0.00	0.00	0.997
Tension	12	586.206	48.85	21.99	<.001
Location.Soil_type	1	275.310	275.31	123.90	<.001
Location.Tension	12	19.878	1.66	0.75	0.704
Soil_type.Tension	12	1.856	0.16	0.07	1
Location.Soil_type.Tension	12	40.585	3.38	1.52	0.128
Residual	104	231.085	2.22		
Total	155	1246.582			

Table 57: ANOVA of moisture ratio for similar peats from West Sedgemoor and Methwold Fen (Humified and Semi-fibrous Peats).

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	604.2	604.217	404.51	<.001
Residual	115	171.8	1.494		
Total	116	776	6.69		
	Percentage variance accounted for 77.7				

Table 58: Regression analysis of West Sedgemoor shrinkage characteristics.

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	477	476.978	387.14	<.001
Residual	115	141.7	1.232		
Total	116	618.7	5.333		
	Percentage variance accounted for 76.9				

Table 59: Regression analysis of Methwold Fen shrinkage characteristics.

E.10 Water retention characteristics

Soil type	Tension (m)	Average	n	SD	SE	95% CI
Peaty Loam	0	86.055	3	1.59	0.92	3.96
Peaty Loam	-0.2	80.293	3	2.76	1.59	6.85
Peaty Loam	-0.4	78.917	3	3.36	1.94	8.34
Peaty Loam	-0.6	77.711	3	4.02	2.32	9.99
Peaty Loam	-0.8	76.706	3	4.45	2.57	11.07
Peaty Loam	-1.0	75.784	3	4.90	2.83	12.18
Peaty Loam	-10	62.769	3	7.89	4.56	19.61
Peaty Loam	-20	57.889	3	7.64	4.41	18.97
Peaty Loam	-40	55.073	3	6.96	4.02	17.29
Peaty Loam	-80	47.077	3	5.01	2.89	12.45
Peaty Loam	-100	47.235	3	5.21	3.01	12.94
Peaty Loam	-150	46.155	3	6.29	3.63	15.62
Humified	0	90.693	3	2.53	1.46	6.28
Humified	-0.2	84.354	3	0.54	0.31	1.35
Humified	-0.4	81.340	3	0.98	0.57	2.44
Humified	-0.6	79.149	3	1.19	0.69	2.96
Humified	-0.8	77.422	3	1.33	0.77	3.32
Humified	-1.0	75.617	3	1.51	0.87	3.74
Humified	-10	71.605	3	3.83	2.21	9.51
Humified	-20	55.477	3	6.70	3.87	16.64

Humified	-40	51.751	3	7.24	4.18	17.99
Humified	-80	49.334	3	7.65	4.42	19.01
Humified	-100	46.764	3	8.67	5.01	21.54
Humified	-150	45.327	3	8.11	4.68	20.15
Semi-fibrous	0	87.880	3	1.26	0.73	3.14
Semi-fibrous	-0.2	77.753	3	0.81	0.47	2.01
Semi-fibrous	-0.4	73.802	3	0.96	0.55	2.39
Semi-fibrous	-0.6	69.582	3	1.27	0.73	3.16
Semi-fibrous	-0.8	65.733	3	1.77	1.02	4.41
Semi-fibrous	-1.0	62.087	3	1.98	1.14	4.91
Semi-fibrous	-10	58.129	3	6.56	3.78	16.28
Semi-fibrous	-20	48.204	3	7.07	4.08	17.57
Semi-fibrous	-40	43.823	3	6.56	3.79	16.30
Semi-fibrous	-80	42.921	3	2.59	1.50	6.44
Semi-fibrous	-100	40.711	3	2.02	1.17	5.02
Semi-fibrous	-150	37.763	3	3.75	2.16	9.31

Table 60: Water retention characteristics for West Sedgemoor peats.

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	17122	17121.5	163.86	<.001
Residual	106	11076	104.5		
Total	107	28197	263.5		
R^2= 60.4					

Table 61: Linear regression of soil moisture against pressure potential for West Sedgemoor peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_Type	2	1443.56	721.78	30.94	<.001
Pressure potential (m)	11	24635.84	2239.62	96.02	<.001
Soil_Type.Tension_cm	22	438.30	19.92	0.85	0.651
Residual	72	1679.39	23.32		
Total	107	28197.09			
LSDs: Soil type = 2.269, Tension = 4.538 and Soil type*Tension = 7.86					

Table 62: ANOVA of Water Retention Characteristics for West Sedgemoor peats.

Soil type	**Tension (M)**	**Average**	**n**	**SD**	**SE**	**95% CI**
Amorphous	0	81.451	3	4.67	2.70	11.60
Amorphous	-0.2	71.078	3	3.34	1.93	8.30
Amorphous	-0.4	64.319	3	3.11	1.79	7.72
Amorphous	-0.6	60.407	3	2.73	1.57	6.78
Amorphous	-0.8	58.329	3	2.58	1.49	6.42
Amorphous	-1.0	56.338	3	2.55	1.47	6.33
Amorphous	-10	48.286	3	4.19	2.42	10.41
Amorphous	-20	47.102	3	4.14	2.39	10.29
Amorphous	-40	46.139	3	4.12	2.38	10.24
Amorphous	-80	44.484	3	2.97	1.72	7.38
Amorphous	-100	41.063	3	3.85	2.22	9.57
Amorphous	-150	40.490	3	3.86	2.23	9.59
Semi-fibrous	0	90.025	3	3.25	1.87	8.06
Semi-fibrous	-0.2	81.893	3	5.98	3.45	14.87
Semi-fibrous	-0.4	76.057	3	6.64	3.83	16.49

Semi-fibrous	-0.6	72.421	3	6.86	3.96	17.03
Semi-fibrous	-0.8	70.007	3	6.97	4.03	17.33
Semi-fibrous	-1.0	67.266	3	7.01	4.05	17.41
Semi-fibrous	-10	66.699	3	7.84	4.53	19.48
Semi-fibrous	-20	50.615	3	5.61	3.24	13.95
Semi-fibrous	-40	48.625	3	6.68	3.86	16.60
Semi-fibrous	-80	46.866	3	7.38	4.26	18.33
Semi-fibrous	-100	45.238	3	8.35	4.82	20.75
Semi-fibrous	-150	44.887	3	8.87	5.12	22.05
Fibrous	0	88.983	3	4.27	2.47	10.61
Fibrous	-0.2	75.640	3	10.14	5.86	25.20
Fibrous	-0.4	72.000	3	11.21	6.47	27.85
Fibrous	-0.6	68.842	3	11.75	6.78	29.20
Fibrous	-0.8	66.567	3	11.92	6.88	29.61
Fibrous	-1.0	64.142	3	11.87	6.85	29.48
Fibrous	-10	58.774	3	10.35	5.98	25.72
Fibrous	-20	49.158	3	10.37	5.99	25.76
Fibrous	-40	46.582	3	10.33	5.96	25.66
Fibrous	-80	44.086	3	10.16	5.87	25.25
Fibrous	-100	42.723	3	9.44	5.45	23.45
Fibrous	-150	42.169	3	10.33	5.96	25.66

Table 63: Water retention characteristics for Methwold Fen peats.

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	11883	11883.1	86.94	<.001
Residual	106	14488	136.7		
Total	107	26371	246.5		
R^2=44.5					

Table 64: Linear regression of soil moisture against pressure potential for Methwold Fen peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_Type	2	1293.84	646.92	11.54	<.001
Pressure potential (m)	11	20568.42	1869.86	33.36	<.001
Soil_Type.Tension	22	473.1	21.50	0.38	0.993
Residual	72	4035.53	56.05		
Total	107	26370.89			
LSDs: Soil type = 3.518, Tension = 7.037 and Soil type*Tension = 12.19					

Table 65: ANOVA for Water Retention Characteristics of Methwold Fen peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	589.56	589.56	23.06	<.001
Soil_Type	1	0.03	0.03	0	0.973
Tension_cm	11	30292.84	2753.89	107.74	<.001
Location.Soil_Type	1	2539.74	2539.74	99.36	<.001
Location.Tension_cm	11	373.7	33.97	1.33	0.22
Soil_Type.Tension_cm	11	134.33	12.21	0.48	0.913
Location.Soil_Type.Tension_cm	11	446.81	40.62	1.59	0.114
Residual	96	2453.86	25.56		
Total	143	36830.87			

LSDs: Soil type and Location = 1.673; Tension = 4.10 and Soil type*Location*Tension = 8.19

Table 66: ANOVA of Water Retention Characteristics for like peat types from Methwold Fen and West Sedgemoor.

E.11 Hydraulic Conductivity

Saturated Hydraulic Conductivity (Ksat)

Site	Field	K value (m/d)
WSM	1	1.34
WSM	4	0.7
WSM	5	1.22
WSM	1	0.32
WSM	2	0.24
WSM	3	0.41
WSM	4	0.45
WSM	5	0.45
WSM	6	0.38
WSM	7	0.42
WSM	8	0.28
WSM	9	0.64
WSM	10	1.69
WSM	11	3.57
WSM	12	0.29
WSM	13	0.57
Average 0.811 m d^{-1}		

Table 67: Field derived saturated hydraulic conductivity for West Sedgemoor peats.

Horizon	Soil type	Ksat m d^{-1} (Horizontal)	n	SD	SE	95%CI
A	Peaty Loam	1.511	27	0.56	0.11	0.22
B	Humified	1.551	27	2.06	0.40	0.83
C	Semi-fibrous	2.296	27	2.00	0.39	0.81

Table 68:West Sedgemoor laboratory calculated saturated lateral hydraulic conductivity.

$$K_{sat}(\text{horiz}) = \frac{(1.51\times0.12)+(1.55\times0.57)+(2.30\times0.31)}{(0.12+0.57+0.31)} = 1.77\text{m d}^{-1}$$

Equation 40: West Sedgemoor weighted mean saturated lateral hydraulic conductivity in upper metre of peat.

Horizon	Horizon	Ksat m d^{-1} (vertical)	n	SD	SE	95%CI
A	Peaty Loam	0.244	26	0.30	0.06	0.12
B	Humified	0.137	26	0.05	0.01	0.02
C	Semi-fibrous	1.099	26	0.52	0.10	0.21

Table 69: West Sedgemoor laboratory calculated saturated vertical hydraulic conductivity**.**

$$1/K_{sat}\,(\text{vert}) = \frac{(0.12/0.24 + 0.57/0.14 + 0.31/1.1)}{(0.12 + 0.57 + 0.31)} \approx 0.21\text{m d}^{-1}$$

Equation 41: West Sedgemoor weighted mean vertical saturated hydraulic conductivity in upper metre of peat.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Plane	1	67.669	67.669	45.4	<.001
Soil_Type	2	25.235	12.617	8.47	<.001
Plane.Soil_Type	2	0.328	0.164	0.11	0.896
Residual	156	232.497	1.49		
Total	161	325.728			
LSDs: soil type = 0.464, Plane = 0.379 and Soil type*Plane = 0.656					

Table 70: ANOVA of saturated hydraulic conductivity for West Sedgemoor peats.

Horizon	Soil type	Ksat m d^{-1} (Horizontal)	n	SD	SE	95%CI
A/B	Amorphous	0.27	27	0.11	0.02	0.04
C	Semi-fibrous	2.12	27	0.61	0.12	0.25
D	Fibrous	2.95	9	0.05	0.02	0.04

Table 71: Methwold Fen laboratory calculated saturated horizontal hydraulic conductivity.

$$K_{sat}(\text{horiz}) = \frac{(0.27\times0.39)+(2.12\times0.51)+(2.95\times0.10)}{(0.39+0.51+0.10)} = 1.48\text{m d}^{-1}$$

Equation 42: Methwold Fen weighted mean lateral saturated hydraulic conductivity in upper metre of peat.

Horizon	Soil type	Ksat m d^{-1} (vertical)	n	SD	SE	95%CI
A/B	Amorphous	0.22	27	0.31	0.06	0.12
C	Semi-fibrous	0.25	9	0.01	0.00	0.01
D	Fibrous	0.43	27	0.13	0.02	0.05

Table 72: Methwold Fen laboratory calculated saturated vertical hydraulic conductivity.

$$1/K_{sat}\,(\text{vert}) = \frac{(0.39/0.22 + 0.51/0.25 + 0.10/0.43)}{(0.39 + 0.51 + 0.10)} \approx 0.25\text{m d}^{-1}$$

Equation 43: Methwold Fen weighted mean vertical saturated hydraulic conductivity in upper metre of peat.

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Plane	1		88.171	88.1705	824.3	<.001
Soil_Type	2		58.067	29.0334	271.43	<.001
Plane.Soil_Type	2		44.329	22.1645	207.21	<.001
Residual	120	-36	12.836	0.107		
Total	125	-36	123.72			
LSDs: Soil type 0.125, Plane 0.102 and Soil type*plane 0.176						

Table 73: ANOVA of saturated hydraulic conductivity for Methwold Fen peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	13.694	13.694	3.33	0.069
Plane	1	0.283	0.283	0.07	0.793
Soil_Type	1	65.668	65.668	15.99	<.001
Location.Plane	1	82.101	82.101	19.99	<.001
Location.Soil_Type	1	206.651	206.651	50.31	<.001
Plane.Soil_Type	1	16.21	16.21	3.95	0.048
Location.Plane.Soil_Type	1	23.23	23.23	5.66	0.018
Residual	208	854.39	4.108		
Total	215	1262.227			
LSDs: Soil type, Plane and Location = 0.544 and Soil type*Plane*Location = 1.087					

Table 74: ANOVA of saturated hydraulic conductivity for similarly classified peats from West Sedgemoor and Methwold Fen (humified and semi-fibrous peats).

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	1.37	1.37	92.72	0.002
Residual	3	0.04	0.01		
Total	4	1.41	0.35		
Percentage variance accounted for 95.8					

Table 75: Regression analysis of relationship between hydraulic conductivity and pore size.

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.93	0.93	5.86	0.094
Residual	3	0.48	0.16		
Total	4	1.41	0.35		
Percentage variance accounted for 66					

Table 76: Regression analysis of relationship between hydraulic conductivity and specific yield.

Unsaturated Saturated Hydraulic Conductivity (K(ψ))

Pressure Pressure (m)	Unsaturated hydraulic conductivity (cm s^{-1})		
	Peaty Loam	Humified	Semi-Fibrous
0.001	2.82E-04	1.59E-04	1.27E-03
0.01	1.71E-04	8.77E-05	5.13E-04
0.1	6.12E-05	2.76E-05	8.00E-05
0.2	3.03E-05	1.27E-05	2.46E-05
0.3	1.71E-05	6.87E-06	1.05E-05
0.4	1.06E-05	4.11E-06	5.38E-06
0.5	6.92E-06	2.64E-06	3.12E-06
0.75	2.90E-06	1.08E-06	1.10E-06
1	1.46E-06	5.38E-07	5.08E-07
2	2.35E-07	8.71E-08	7.47E-08
4	3.28E-08	1.25E-08	1.05E-08
8	4.29E-09	1.71E-09	1.45E-09
10	2.21E-09	8.95E-10	7.64E-10

Table 77: West Sedgemoor calculated unsaturated hydraulic conductivity (based on van Genuchten parameters from Water Retention Curve and vertical saturated hydraulic conductivity).

$$1/K(\Psi(-1.0\mathrm{m})) = \frac{\left(\frac{0.12}{1.47\times10^{-3}}\right)+\left(\frac{0.57}{2.95\times10^{-3}}\right)+\left(\frac{0.31}{3.23\times10^{-2}}\right)}{0.12+0.57+0.31} = 3.516\times10^{-3}\mathrm{m\ d}^{-1}$$

Equation 44: West Sedgemoor weighted mean vertical unsaturated hydraulic conductivity (based on van Genuchten parameters for determining K_{unsat} of a soil type/horizon and the experienced pressure potential at the mid-point of that soil horizon, assuming a -1.0m water table).

Pressure potential (m)	Unsaturated hydraulic conductivity (cm s^{-1})		
	Amorphous	Semi-Fibrous	Fibrous
0.001	2.55E-04	2.89E-04	4.98E-04
0.01	1.02E-04	1.36E-04	1.92E-04
0.1	1.00E-05	2.47E-05	2.30E-05
0.2	2.37E-06	7.96E-06	6.10E-06
0.3	8.73E-07	3.44E-06	2.40E-06
0.4	4.09E-07	1.77E-06	1.17E-06
0.5	2.22E-07	1.02E-06	6.56E-07
0.75	7.07E-08	3.56E-07	2.19E-07
1	3.08E-08	1.63E-07	9.86E-08
2	4.01E-09	2.29E-08	1.37E-08
4	5.08E-10	3.06E-09	1.84E-09
8	6.38E-11	4.01E-10	2.45E-10
10	3.27E-11	2.08E-10	1.28E-10

Table 78: Methwold Fen calculated unsaturated hydraulic conductivity (based on van Genuchten parameters from Water Retention Curve and vertical saturated hydraulic conductivity).

$$1/K(\Psi(-1.0m)) = \frac{\left(\frac{0.39}{5.08\times10^{-5}}\right)+\left(\frac{0.51}{2.97\times10^{-3}}\right)+\left(\frac{0.10}{5.15\times10^{-2}}\right)}{0.39+0.51+0.10} = 1.274\times10^{-4}\,m\,d^{-1}$$

Equation 45: Methwold Fen weighted mean vertical unsaturated hydraulic conductivity (based on van Genuchten parameters for determining Kunsat of a soil type/horizon and the experienced pressure potential at the mid-point of that soil horizon, assuming a -1.0m water table).

E.12 Correlation matrix of physical and hydraulic data.

	Organic Matter (g g-1)	Organic Carbon (g g-1)	Porosity (cm^3 cm^{-3})	Particle Density (g cm^{-3})	Bulk Density (g cm^{-3})	Void Ratio (0.01 Bar)	Void Ratio (1 Bar)
Organic Matter (g g-1)	1.00						
Organic Carbon (g g-1)	**0.99**	1.00					
Porosity cm^3 cm^{-3}	**0.56**	**0.82**	1.00				
Particle Density (g cm^{-3})	**-0.40**	**-0.56**	**-0.40**	1.00			
Bulk Density (g cm^{-3})	**-0.63**	**-0.84**	**-0.76**	**0.55**	1.00		
VR 0.01 Bar	0.19	0.18	0.35	-0.31	-0.39	1.00	
VR 1 Bar	0.13	0.11	0.21	-0.28	-0.27	**0.97**	1.00
VR 15 Bar	0.03	0.00	0.11	-0.27	-0.13	**0.91**	**0.97**
MR 0.01 Bar	0.01	0.00	0.18	-0.23	-0.24	**0.97**	**0.95**
MR 1 Bar	0.06	0.05	0.22	-0.18	-0.28	**0.93**	**0.93**
MR 15 Bar	-0.02	-0.04	0.10	-0.09	-0.16	**0.87**	**0.90**
K horiz' (m d^{-1})	0.14	0.20	0.14	-0.24	**-0.64**	**0.62**	0.48
K vert' (m d^{-1})	-0.21	-0.21	-0.04	0.05	-0.10	**0.55**	**0.51**
	Void Ratio (15 Bar)	**Moisture Ratio (0.01 Bar)**	**Moisture Ratio (1 Bar)**	**Moisture Ratio (15 Bar)**	**Khoriz' (m d^{-1})**	**Kvert' (m d^{-1})**	
Organic Matter (g g-1)							
Organic Carbon (g g-1)							
Porosity cm^3 cm^{-3}							
Particle Density (g cm^{-3})							
Bulk Density (g cm^{-3})							
VR 0.01 Bar							
VR 1 Bar							
VR 15 Bar	1.00						
MR 0.01 Bar	**0.91**	1.00					
MR 1 Bar	**0.91**	**0.93**	1.00				
MR 15 Bar	**0.91**	**0.91**	**0.95**	1.00			
K horiz' (m d^{-1})	0.36	**0.60**	**0.59**	**0.52**	1.00		
K vert' (m d^{-1})	0.42	**0.66**	**0.66**	**0.66**	**0.62**	1.00	

Table 79: Correlation matrix of physical and hydraulic parameters of low-lying agricultural peat soils.

F Tables of data for microbial and chemical analyses.

F.1 Field and soil core respiration data tables and analyses

Irrigation spacing	10	25	40		
$\mu g\ CO_2$-C $m^2\ hr^{-1}$	9.68	5.26	5.47		
SE: 1.67					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	2	111.76	56	2.22	0.131
Residual	24	604.67	25		
Total	26	716.43			
LSD: 4.88					

Table 80: Mean below surface respiration from sites under different water management at West Sedgemoor during summer 2003 and ANOVA Lysimeter data tables and analyses.

Month	Drained	Flooded	Intermediate		
January	0.02	0.42	0.35		
February	0.00	0.41	0.32		
March	1.44	1.01	0.68		
April	1.63	1.58	1.29		
May	1.04	0.97	0.87		
June	1.82	1.23	1.46		
July	1.78	1.26	1.38		
October	0.02	1.48	0.83		
November	0.00	0.65	0.49		
December	0.00	0.36	0.22		
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Month	9	47.67	5.30	133.04	<.001
Treatment	2	0.96	0.48	12.08	<.001
Month.Treatment	18	12.49	0.69	17.43	<.001
Residual	150	5.97	0.04		
Total	179	67.10			
LSD: 0.228					

Table 81: Averages of West Sedgemoor lysimeter CO_2-C respiration (g m^{-2}) and ANOVA of lysimeter CO_2-C evolution data.

Month	Drained	Flooded	Intermediate		
January	0.01	0.12	0.10		
February	0.00	0.10	0.08		
March	0.41	0.29	0.19		
April	0.45	0.43	0.35		
May	0.29	0.28	0.24		
June	0.50	0.34	0.40		
July	0.51	0.36	0.39		
August	0.51	0.36	0.39		
September	0.25	0.38	0.30		
October	0.01	0.42	0.24		
November	0.00	0.18	0.14		
December	0.00	0.10	0.06		
Totals	**2.91**	**3.34**	**2.89**		
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Month	11	4.32	0.39	110.56	<.001
Treatment	2	0.06	0.03	9.03	<.001
Month.Treatment	22	1.11	0.05	14.18	<.001
Residual	180	0.64	0.00		
Total	215	6.13			
LSD: 0.07					

Table 82: Averages of calculated West Sedgemoor lysimeter organic matter loss in tonnes organic matter ha^{-1} $month^{-1}$ and ANOVA of monthly loss of organic matter (t ha^{-1}).

Month	Drained	Flooded	Intermediate		
January	0.048	0.12	0.2		
February	0.21	0.30	0.243		
March	0.627	0.45	0.293		
April	1.06	0.52	0.623		
May	0.952	0.36	0.542		
June	1.563	0.62	0.943		
July	1.673	0.76	1.057		
October	0.578	0.40	0.445		
November	0.347	0.22	0.322		
December	0.175	0.23	0.143		
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Month	9	20.54	2.28	112.72	<.001
Treatment	2	3.47	1.73	85.69	<.001
Month.Treatment	18	4.63	0.26	12.71	<.001
Residual	150	3.04	0.02		
Total	179	31.67			
LSD: 0.162					

Table 83: Averages of Methwold Fen lysimeter CO_2-C respiration (g m^{-2}) and ANOVA of lysimeter CO_2-C evolution data.

Month	Drained	Flooded	Intermediate		
January	0.0183	0.04	0.0717		
February	0.0667	0.0967	0.08		
March	0.2267	0.1617	0.105		
April	0.3683	0.18	0.2167		
May	0.3417	0.1283	0.1933		
June	0.5417	0.2133	0.3267		
July	0.5983	0.2733	0.38		
August	0.5983	0.2733	0.38		
September	0.2	0.14	0.1517		
October	0.2067	0.1433	0.16		
November	0.1183	0.0783	0.1117		
December	0.0633	0.0817	0.0517		
Totals	3.35	1.81	2.23		
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Month	11	3.47	0.32	99.33	<.001
Treatment	2	0.63	0.32	99.51	<.001
Month.Treatment	22	0.71	0.03	10.18	<.001
Residual	180	0.57	0.00		
Total	215	5.39			
LSD 0.06					

Table 84: Averages of calculated Methwold Fen lysimeter organic matter loss (tonnes organic matter ha^{-1} $month^{-1}$) and ANOVA of monthly loss of organic matter (t ha^{-1}).

F.2 Fatty acids identified in this work

Fatty acid	Retention time (mins)	WSM 10 m spaced sub-irrigation Horizon abundance (%)			WSM 25 m spaced sub-irrigation Horizon abundance (%			WSM 40 m spaced sub-irrigation Horizon abundance (%)		
		1	2	3	1	2	3	1	2	3
14:0	14.73	1.31	1.86	1.88	1.55	2.59	1.36	1.80	1.34	1.06
i 15:0	16.46	8.45	8.80	6.63	7.97	10.18	5.19	7.88	7.31	3.98
ai 15:0	16.70	6.22	7.16	7.92	7.06	10.19	7.79	7.53	7.17	4.79
15:0	17.55	1.48	0.62	0.93	1.14	0.79	0.82	1.17	0.62	0.66
i 16:0	19.56	9.34	2.66	2.72	9.38	3.23	4.68	7.80	3.17	1.48
ai 16:0	19.90	0.16	--	--	0.14	--	--	0.53	1.68	1.22
16:1ω9	20.12	0.22	0.49	0.24	0.15	0.30	0.51	2.07	7.91	11.96
16:1ω5	20.43	0.13	--	--	0.10	0.16	0	0.64	1.42	0.86
16:0	20.81	15.74	19.38	23.66	15.23	14.34	23.63	15.38	14.18	20.02
Me17:0isomer (1)	22.15	1.02	3.41	8.78	0.61	4.25	11.49	2.14	5.11	4.92
Me 17:0 isomer (2)	22.31	9.05	9.87	7.41	13.72	10.29	3.07	10.75	11.87	8.97
i 17:0	23.00	3.01	2.19	1.51	2.16	2.39	2.14	2.53	2.73	1.51
ai 17:0	23.31	2.86	2.40	3.05	2.62	2.69	5.64	3.47	2.19	1.78
cys 17:0	23.81	4.83	5.99	7.88	6.32	6.39	8.93	5.18	5.63	7.72
17:1 isomer	24.08	0.70	0.70	0.90	0.77	0.43	1.40	0.98	0.38	0.56

17:0	24.33	0.83	0.76	1.15	0.88	1.58	0.84	0.63	0.83	
17:0 isomer	24.47	2.17	0.64	0.65	2.64	1.03	0.61	2.81	1.62	0.59
2-OH 16:0	25.06	0.38	0.36	0.88	0.40	0.35	1.89	0.24	0.19	0.48
18:0 isomer	25.84	3.08	0.37	--	3.23	0.51	--	2.27	0.50	--
18:2w6 c	26.83	--	--	--	--	--	--	1.83	0.77	1.64
18:1ω7t	27.47	0.66	0.63	0.16	0.49	0.31	--	0.43	0.67	1.00
18:0	28.05	4.94	4.17	5.20	2.97	5.02	6.12	3.56	4.02	3.63
19:2	29.53	3.37	1.52	1.79	4.85	2.74	1.84	3.92	2.26	1.32
cyc-19:0	31.32	20.38	24.57	14.08	14.66	18.42	10.24	14.16	15.81	17.80
20:0	35.63	0.70	0.96	1.25	0.63	1.47	1.92	0.63	0.78	0.78

Table 85: Fatty acids identified at West Sedgemoor, their approximate retention times and relative abundance.

Fatty acid	Retention time (mins)	MF Field 1 Horizon abundance (%)			MF Field 2 Horizon abundance (%			MF Field 2 Horizon abundance (%)		
		1	2	3	1	2	3	1	2	3
14:0	14.73	1.63	1.65	1.51	1.63	1.50	1.47	1.16	1.43	1.91
i 15:0	16.46	9.71	9.61	9.74	10.21	8.22	7.92	7.05	8.14	9.17
ai 15:0	16.70	6.42	5.17	5.82	7.56	6.82	8.41	5.28	5.66	7.05
15:0	17.55	0.87	0.90	0.49	1.07	0.79	0.58	0.73	0.54	0.62
i 16:0	19.56	4.20	2.56	2.71	4.31	3.39	2.81	3.27	2.53	2.51
ai 16:0	19.90	--	0.95	0.45	0.20	2.09	2.22	1.67	1.45	1.19
16:1ω9	20.12	0.33	0.54	0.50	0.26	9.67	9.63	6.07	7.13	5.06
16:1ω5	20.43	0.13	--	--	0.11	2.35	1.93	1.45	1.71	1.80
16:0	20.81	18.96	20.57	19.45	17.57	14.30	15.30	18.18	17.50	17.03
Me17:0isomer (1)	22.15	2.00	8.27	6.31	2.04	4.23	3.33	4.65	4.14	4.72
Me 17:0 isomer (2)	22.31	7.18	5.77	6.75	8.14	9.02	10.05	5.64	5.86	5.85
i 17:0	23.00	2.70	3.08	2.98	2.64	2.50	2.55	2.69	2.51	2.42
ai 17:0	23.31	2.70	3.35	2.88	3.01	2.37	1.96	2.33	1.93	2.45
cys 17:0	23.81	9.71	6.67	8.56	7.79	5.13	6.19	7.50	9.24	7.68
17:1 isomer	24.08	0.40	1.07	0.75	0.37	0.28	0.33	0.40	0.36	0.45
17:0	24.33	0.78	1.11	1.11	1.04	0.79	0.54	0.86	0.56	0.70
17:0 isomer	24.47	2.20	2.01	2.15	3.02	2.36	1.57	1.82	1.22	1.18
2-OH 16:0	25.06	0.30	0.50	0.48	0.44	0.13	0.19	0.27	0.23	0.42
18:0 isomer	25.84	1.68	0.31	0.42	1.79	0.96	0.56	1.29	0.42	0.43
18:2w6 c	26.83	--	--	--	12.10	0.32	1.12	1.70	2.68	0.81
18:1ω7t	27.47	0.95	0.40	0.42	0.48	1.34	1.20	0.86	1.65	1.15
18:0	28.05	4.10	5.79	5.01	3.63	3.89	4.02	5.71	6.66	5.45
19:2	29.53	3.06	2.25	2.19	3.23	1.84	1.80	2.83	1.56	1.71
cyc-19:0	31.32	17.60	13.73	15.34	14.00	14.34	12.65	15.06	12.38	16.17
20:0	35.63	1.57	1.77	1.63	0.88	0.95	1.08	1.74	1.42	1.23

Table 86: Fatty acids identified at Methwold Fen (MF), their approximate retention times and relative abundance.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	274.68	137.34	10.18	0.001
Irrigation spacing (m)	2	35.47	17.74	1.31	0.293
Soil_type.Irrigation spacing_m	4	161.48	40.37	2.99	0.047
Residual	18	242.81	13.49		
Total	26	714.44			
LSD: 6.3					

Table 87: West Sedgemoor ANOVA of total bacterial abundance.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	77.290	38.650	3.550	0.050
Irrigation_spacing_m	2	98.820	49.410	4.540	0.025
Soil_type.Irrigation_spacing_m	4	145.200	36.300	3.330	0.033
Residual	18	195.990	10.890		
Total	26	517.300			
LSD: 5.7					

Table 88: West Sedgemoor ANOVA of G-negative and some G-positive anaerobic bacteria.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	507.29	253.64	52.65	<0.001
Irrigation_spacing_m	2	75.41	37.70	7.83	0.001
Soil_type.Irrigation_spacing_m	4	66.97	16.74	3.48	0.03
Residual	18	86.71	4.82		
Total	26	736.38			
LSD: 3.8					

Table 89: West Sedgemoor ANOVA of G-positive bacteria.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	3	19.38	6.46	0.88	0.47
Field_number	2	18.29	9.14	1.24	0.31
Soil_type.Field_number	6	165.57	27.60	3.75	0.01
Residual	24	176.39	7.35		
Total	35	379.62			
LSD: 4.57					

Table 90: Methwold Fen ANOVA of total bacterial abundance.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	3	51.65	17.22	1.81	0.17
Field_number	2	79.99	39.99	4.19	0.03
Soil_type.Field_number	6	105.09	17.51	1.84	0.13
Residual	24	228.88	9.54		
Total	35	465.599			
LSD: 5.2					

Table 91: Methwold Fen ANOVA of G-negative and some G-positive anaerobic bacteria.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	3	22.70	7.57	2.55	0.08
Field_number	2	102.02	51.01	17.16	<.001
Soil_type.Field_number	6	50.80	8.47	2.85	0.03
Residual	24	71.33	2.97		
Total	35	246.85			
LSD: 2.9					

Table 92: Methwold Fen ANOVA of G-positive bacteria.

Sub Irrigation spacing (m)	Soil horizon	Average PC1	Average PC2	Average PC3
25	Peaty loam	-6.34 (3, 0.51)	4.58 (3, 0.76)	4.01 (3, 1.00)
25	Humified	-3.80 (3, 5.49)	1.05 (3, 1.49)	-2.27 (3, 1.30)
25	Semi fibrous	12.84 (3, 0.69)	3.87 (3, 0.63)	1.69 (3, 0.64)
10	Peaty loam	-6.04 (3, 0.63)	3.12 (3, 0.36)	-1.65 (3, 0.65)
10	Humified	-2.44 (3, 0.35)	-1.28 3, 0.42)	-8.50 (3, 1.57)
10	Semi fibrous	8.08 (3, 0.51)	2.15 (3, 0.31)	-1.81 (3, 0.59)
40	Peaty loam	-3.60 (3, 0.66)	2.61 (3, 1.67)	3.87 (3, 1.43)
40	Humified	-2.22 (3, 0.41)	-5.65 (3, 0.17)	3.38 (3, 0.23)
40	Semi fibrous	3.52 (3, 0.52)	-10.45 (3, 0.66)	1.27 (3, 0.18)

Table 93: West Sedgemoor: 3 principal components accounting for 78 % of variation in PLFAs. Sample size and standard error of the mean are in parentheses.

Field Number	Horizon	Average PC1	Average PC2	Average PC5
1	Amorphous	-5.35 (3, 0.42)	0.32 (3, 1.08)	-0.44 (3, 1.55)
1	Semi fibrous	-3.46 (3, 0.55)	-5.47 (3, 1.69)	1.35 (3, 0.82)
1	Fibrous	-4.20 (3, 0.37)	-3.25 (3, 0.29)	1.21 (3, 1.68)
2	Amorphous	-3.95 (3, 0.62)	3.67 (3, 2.75)	1.30 (3, 2.52)
2	Semi fibrous	5.92 (3, 0.31)	1.67 (3, 0.14)	0.90 (3, 0.21)
2	Fibrous	6.42 (3, 0.53)	2.50 (3, 0.07)	1.68 (3, 0.74)
3	Amorphous	1.89 (3, 3.30)	-1.69 (3, 1.54)	-1.89 (3, 2.01)
3	Semi fibrous	4.07 (3, 0.41)	-0.79 (3, 0.54)	-0.44 (3, 0.46)
3	Fibrous	0.72 (3, 3.18)	-1.09 (3, 0.08)	-0.54 (3, 0.42)

Table 94: Methwold Fen: 3 Principal components accounting for 70 % of variation in PLFAs. Sample size and standard error of the mean are in parentheses.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Source	1	14.29	14.29	1.18	0.284
Soil_type	5	128.87	25.77	2.14	0.085
Field_Number	2	150.6	75.3	6.24	0.005
Source.Field_Number	2	17.78	8.89	0.74	0.486
Soil_type.Field_Number	10	187.11	18.71	1.55	0.166
Residual	33	398.04	12.06		
Total	53	896.7			
LSD: 3.5					

Table 95: Differences in total bacterial count between West Sedgemoor and Methwold Fen peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	274.68	137.34	10.18	0.00
Irrigation_spacing_m	2	35.47	17.74	1.31	0.29
Soil_type.Irrigation_spacing_m	4	161.48	40.37	2.99	0.05
Residual	18	242.81	13.49		
Total	26	714.44			
LSD: 6.3					

Table 96: ANOVA of differences in relative abundance of total bacterial count at West Sedgemoor.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	77.29	38.65	3.55	0.05
Irrigation_spacing_m	2	98.82	49.41	4.54	0.03
Soil_type.Irrigation_spacing_m	4	145.20	36.30	3.33	0.03
Residual	18	195.99	10.89		
Total	26	517.30			
LSD: 5.7					

Table 97: ANOVA of relative abundance of G-negative and anaerobic G-positive bacteria at West Sedgemoor.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	2	507.29	253.64	52.65	<.001
Irrigation_spacing_m	2	75.41	37.70	7.83	0.00
Soil_type.Irrigation_spacing_m	4	66.97	16.74	3.48	0.03
Residual	18	86.71	4.82		
Total	26	736.38			
LSD: 3.8					

Table 98: ANOVA of relative abundance of G-positive bacterial at West Sedgemoor.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	3	19.38	6.46	0.88	0.47
Field_number	2	18.29	9.14	1.24	0.31
Soil_type.Field_number	6	165.57	27.60	3.75	0.01
Residual	24	176.39	7.35		
Total	35	379.62			
LSD: 4.57					

Table 99: ANOVA of relative abundance of total bacterial count in Methwold Fen peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	3	51.65	17.22	1.81	0.17
Field_number	2	79.99	39.99	4.19	0.03
Soil_type.Field_number	6	105.09	17.51	1.84	**0.13**
Residual	24	228.88	9.54		
Total	35	465.599			
LSD: 5.2					

Table 100: ANOVA of relative abundance of G-negative and some G-positive anaerobes in Methwold Fen peats.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Soil_type	3	22.70	7.57	2.55	0.08
Field_number	2	102.02	51.01	17.16	<.001
Soil_type.Field_number	6	50.80	8.47	2.85	0.03
Residual	24	71.33	2.97		
Total	35	246.85			
LSD: 2.9					

Table 101: ANOVA of relative abundance of G-positive bacteria in Methwold Fen peats.

F.3 Microbial biomass

	Tension (m)			
Soil_type	0.1	0.5	1	10
humified	1.3	1.2	1.3	1.0
peaty loam	1.7	1.6	1.5	1.2
semi fibrous	1.4	1.0	1.1	0.9

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Soil_type	2		1.81	0.90	31.82	<.001
tension	3		1.58	0.53	18.54	<.001
Soil_type.tension	6		0.21	0.03	1.21	0.317
Residual	47	-1	1.33	0.03		
Total	58	-1	4.90			
LSD: 0.21						

Table 102: Biomass-C in West Sedgemoor peats (mg Biomass-C g $soil^{-1}$) and ANOVA of Biomass-C.

	Tension (m)			
Soil_type	0.1	0.5	1	10
Amorphous	2.0	1.9	1.9	0.9
fibrous	1.6	1.2	1.3	1.1
semi fibrous	1.5	1.2	1.5	1.2

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Soil_type	2		1.70	0.85	16.65	<.001
tension	3		3.41	1.14	22.29	<.001
Soil_type.tension	6		2.02	0.34	6.61	<.001
Residual	45	-3	2.29	0.05		
Total	56	-3	9.03			
LSD: 0.29						

Table 103: Biomass-C in Methwold Fen peats. (mg Biomass-C g $soil^{-1}$) and ANOVA of Biomass-C.

G Tables of meteorological data analysis

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	2.59	1.47	1.16	1.38	1.35	1.20	1.81	1.67	0.72	2.74	1.58	2.17
Potential ET (mm)	0.53	0.68	1.22	2.01	2.54	3.19	2.87	2.88	1.89	1.26	0.56	0.42
Change in soil moisture (mm)	2.06	0.80	-0.07	-0.63	-1.19	-1.99	-1.06	-1.21	-1.16	1.48	1.02	1.75
n	124	116	124	120	124	120	124	124	120	124	120	124

Table 104: Averaged daily weather data (each month) for West Sedgemoor in 2003/04.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	3.01	1.17	0.72	1.28	1.42	2.59	1.72	2.18	0.85	2.27	2.08	1.42
Potential ET (mm)	0.33	0.59	1.01	1.69	2.34	3.30	3.53	3.47	2.76	1.09	0.48	0.34
Change in soil moisture (mm)	2.68	0.58	-0.29	-0.41	-0.93	-0.71	-1.81	-1.28	-1.91	1.18	1.61	1.08
n	124	116	124	120	124	120	124	124	120	124	120	124

Table 105: Averaged daily weather data (each month) for Methwold Fen in 2003/04.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	1.87	1.87	0.14	0.704
Month	11	462.2	42.02	3.23	<.001
Location*Month	11	110.4	10.03	0.77	0.669
Residual	1438	18693	13		
Total	1461	19267			

LSDs: Month = 0.94, Location = 0.37, Location*Month = 1.32

Table 106: ANOVA of daily rainfall data for 2003/04.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	1.958	1.958	3.31	0.069
Month	11	1741	158.3	267.7	<.001
Location*Month	11	54	4.909	8.3	<.001
Residual	1438	850.4	0.591		
Total	1461	2648			

LSDs: Month = 0.20, Location = 0.07, Location*Month = 0.28

Table 107: ANOVA of daily evapo-transpiration data for 2003/04.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Location	1	0	0	0	0.993
Month	11	2549	231.7	16.64	<.001
Location*Month	11	128.4	11.68	0.84	0.601
Residual	1438	20028	13.93		
Total	1461	22705			

LSDs: Month = 0.97, Location = 0.38, Location*Month = 1.37

Table 108: ANOVA of 2003/04 difference between rainfall and potential evapo-transpiration

H Tables of data for observed water-table levels and soil water properties.

H.1 Observed water-table

Date	Control	10 m spacing	25 m spacing	40 m spacing
18/12/2002	-0.13	0.00	-0.06	-0.08
04/02/2003	-0.08	0.00	-0.03	-0.03
12/02/2003	-0.11	0.04	-0.03	0.01
04/03/2003	-0.10	0.03	-0.02	0.02
18/03/2003	-0.11	-0.04	-0.08	-0.05
21/03/2003	-0.06	0.01	0.06	0.07
02/04/2003	-0.15	-0.02	-0.07	-0.02
15/04/2003	-0.26	-0.01	-0.15	-0.08
30/04/2003	-0.22	0.01	-0.07	-0.02
13/05/2003	-0.16	0.03	-0.04	0.00
30/05/2003	-0.31	-0.05	-0.18	-0.14
10/06/2003	-0.39	-0.02	-0.23	-0.25
01/07/2003	-0.59	-0.14	-0.34	-0.43
10/07/2003	-0.62	-0.10	-0.41	-0.49
07/08/2003	-0.46	-0.18	-0.26	-0.36
05/09/2003	-0.66	-0.10	-0.32	-0.41
12/09/2003	-0.65	-0.09	-0.41	-0.44
14/10/2003	-0.78	-0.09	-0.49	-0.56
13/11/2003	-0.53	0.02	-0.23	-0.25
24/11/2003	-0.43	0.11	-0.12	-0.14
27/11/2003	-0.36	0.11	-0.09	-0.08
03/12/2003	-0.19	0.02	-0.01	-0.06
10/12/2003	-0.24	-0.04	-0.10	-0.07
19/12/2003	-0.30	0.03	-0.03	-0.09
23/12/2003	-0.18	0.03	-0.02	-0.04
07/01/2004	-0.15	0.02	-0.02	-0.03
13/01/2004	-0.10	-0.01	-0.06	-0.05

Table 109: West Sedgemoor mean differences in water level between ditch and field on triplicate sites of 3 differently spaced sub-irrigation systems.

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Drain_spacing	3		2.872383	0.957461	108.29	<.001
Date	67		25.49394	0.380507	43.04	<.001
Drain_spacing.Date	201		3.246877	0.016154	1.83	<.001
Residual	505	-39	4.465022	0.008842		
Total	776	-39	34.48779			
LSDs: drain spacing 0.02, Date 0.07 and Drain*space 0.15						

Table 110: ANOVA of difference between ditch and field water levels at West Sedgemoor during 2003/04.

Date	20 m spaced
18/02/2005	0.940
04/03/2005	0.790
18/03/2005	0.670
01/04/2005	0.677
15/04/2005	0.587
29/04/2005	0.277
13/05/2005	0.200
27/05/2005	-0.393
10/06/2005	-0.287
24/06/2005	-0.315
12/07/2005	-0.182

Table 111: Methwold Fen mean difference in water level between ditch and field on 20 m spaced sub-surface drainage and irrigation system. (Note. Positive values denote higher water level in field and negative values denote a drop in water level from the ditch to the field).

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Dipwell	2	0.001	0.0007	0	0.997
Residual	30	7.437	0.2479		
Total	32	7.439			
LSD: 0.43					

Table 112: Analysis of variance of the change in water-table level between ditch and field for replicate observation dipwells at Methwold Fen.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Date	10	7.35	0.73	179.23	<.001
Residual	22	0.09	0.00		
Total	32	7.44			
LSD: 0.108					

Table 113: ANOVA of the change in water-table level between ditch and field between different observation dates at Methwold Fen.

H.2 Field determined hydraulic conductivity.

Mean Ksat (m/d)	n	SD	SE	95% CI
0.81	16	0.85	0.22	0.46

Table 114: Field measured hydraulic conductivity using auger-hole method at West Sedgemoor.

H.3 Equations for limiting depth and evaporation.

West Sedgemoor

$$c = \frac{1}{-0.75.} \ln\left[\frac{3.516 \times 10^{-3}\,\mathrm{md}^{-1}.}{0.21\mathrm{md}^{-1}}\right] \approx 5.45\ \mathrm{m}^{-1}$$

Equation 46: Gardner's equation re-arranged to calculate the soil specific constant for West Sedgemoor.

$$Z = \frac{1}{5.54} \ln\left[1 + \frac{0.21\mathrm{md}^{-1}}{4.0 \times 10^{-3}\,\mathrm{md}^{-1}}\right] \approx 0.72\mathrm{metres}$$

Equation 47: Depth to water table at which the soil becomes limiting to potential evaporation at West Sedgemoor.

$$E_{\mathrm{lim}} = \frac{0.21}{e^{(5.54 \times 0.5)} - 1} \approx 14\,\mathrm{mm\ \ d}^{-1}$$

Equation 48: limiting evaporation at West Sedgemoor

Methwold Fen

$$c = \frac{1}{-0.75.} \ln\left[\frac{1.274 \times 10^{-4}\,\mathrm{md}^{-1}.}{0.25\mathrm{md}^{-1}}\right] \approx 10.11\ \mathrm{m}^{-1}$$

Equation 49: Gardner's equation re-arranged to calculate the soil specific constant for Methwold Fen.

$$Z = \frac{1}{10.11} \ln\left[1 + \frac{0.25\mathrm{md}^{-1}}{4.0 \times 10^{-3}\,\mathrm{md}^{-1}}\right] \approx 0.41\ \mathrm{metres}$$

Equation 50: Depth to water table at which the soil becomes limiting to potential evaporation.

$$E_{\mathrm{lim}} = \frac{0.25}{e^{(10.11 \times 0.5)} - 1} \approx 1.6\,\mathrm{mm\ \ d}^{-1}$$

Equation 51: limiting evaporation at Methwold Fen.

H.4 Correlations between modelled and observed water-table depth at West Sedgemoor.

Change	d.f.	s.s.	m.s.	v.r.	F pr.
1	1.00	0.00	4.95E-05	1.52	0.23
Residual	23.00	0.00	3.26E-05		
Total	24.00	0.00	3.33E-05		
percentage variance accounted for 2.1					

Table 115: Correlation between modelled and observed difference in water level on 10 m spaced sub-irrigation at West Sedgemoor.

Change	d.f.	s.s.	m.s.	v.r.	F pr.
1	1.00	0.00	0.002414	3.66	0.07
Residual	23.00	0.02	0.00066		
Total	24.00	0.02	0.000733		
percentage variance accounted for 10.0					

Table 116: Correlation between modelled and observed difference in water level on 25 m spaced sub-irrigation at West Sedgemoor.

Change	d.f.	s.s.	m.s.	v.r.	F pr.
1	1.00	0.03	0.029718	15.65	<.001
Residual	23.00	0.04	0.001899		
Total	24.00	0.07	0.003058		
percentage variance accounted for 37.9					

Table 117: Correlation between modelled and observed difference in water level on 40 m spaced sub-irrigation at West Sedgemoor.

Change	d.f.	s.s.	m.s.	v.r.	F pr.
1	1.00	0.13	0.13346	2.15	0.16
Residual	22.00	1.37	0.06208		
Total	23.00	1.50	0.06518		
percentage variance accounted for 4.8					

Table 118: Correlation between modelled and observed difference in water level on Control plot (no sub-irrigation and ditches at 100 m spacings) at West Sedgemoor.

H.5 Hydrostatic pressure potential gradient below the water-table ($m\ m^{-1}$).

Date	10 m spaced	25 m spaced	40 m spaced
05/11/2004	0	0.09	0.04
22/11/2004	-0.04	-0.04	-0.05
10/12/2004	0.01	0.08	0.14
07/01/2005	-0.08	0	0.07
19/01/2005	-0.06	0.03	0.005
04/02/2005	-0.02	0	0.06
18/02/2005	-0.01	-0.03	0
03/03/2005	0	0	0.06
16/03/2005	-0.07	0	0.04
01/04/2005	0	0.05	0.05
14/04/2005	-0.03	0.02	0.02
27/04/2005	-0.01	0	0.04
13/05/2005	-0.06	0.02	-0.05
25/05/2005	0	0	0.05
13/06/2005	0.02	-0.1	0.02
27/06/2005	0.01	0	0.06
08/07/2005	-0.1	-0.04	-0.05

Table 119: Hydrostatic pressure head gradient ($m\ m^{-1}$) from 1.0 to 2.0 m depth on 3 different sub-irrigation systems at West Sedgemoor (Note. positive values indicate downward flow and negative values upward flow).

Date	20 m spaced sub irrigation
18-Feb-05	0.00
04-Mar-05	0.02
18-Mar-05	0.08
01-Apr-05	0.05
15-Apr-05	0.08
29-Apr-05	0.09
13-May-05	0.08
27-May-05	0.03
10-Jun-05	-0.21
24-Jun-05	-0.17
12-Jul-05	-0.14

Table 120: Hydrostatic pressure head gradient ($m\ m^{-1}$) from 1.0 to 2.0 m depth on 20 m spaced sub-irrigation systems at Methwold Fen (Note. positive values indicate downward flow and negative values upward flow).

H.6 Pressure potential gradients in the vadose zone (m m^{-1})

	10 m spaced (m)		25 m spaced (m)		40 m spaced (m)	
Date	0.2 to 0.5	0.5 to 0.8	0.2 to 0.5	0.5 to 0.8	0.2 to 0.5	0.5 to 0.8
05/11/2004	0.07	0.23	0.03	-0.07	0.24	-0.23
22/11/2004	0.00	-0.23	-0.03	0.03	0.07	0.00
10/12/2004	-0.03	0.27	0.00	0.00	0.00	-0.06
07/01/2005	-0.17	0.77	0.03	-0.03	0.31	-0.06
19/01/2005	-0.03	0.00	-0.03	0.00	0.10	-0.03
04/02/2005	0.00	0.03	0.00	0.03	0.00	0.00
18/02/2005	0.00	0.00	0.00	0.00	0.03	-0.03
03/03/2005	0.00	0.00	-0.06	0.00	0.00	0.00
16/03/2005	0.00	0.03	-0.03	0.00	0.00	0.00
01/04/2005	0.13	0.00	-0.03	0.00	0.00	0.00
14/04/2005	0.00	0.07	-0.19	0.03	0.03	0.00
27/04/2005	0.00	0.07	-0.23	0.03	0.03	0.00
13/05/2005	0.03	-0.20	-0.29	0.20	-0.17	-0.03
25/05/2005	0.00	0.03	0.00	0.03	0.07	0.00
13/06/2005	-0.03	0.03	0.10	-0.40	0.31	-0.23
27/06/2005	-0.07	0.03	-0.34	-0.28	1.03	-0.45
08/07/2005	-0.10	0.03	-0.65	-0.29	1.76	-0.68

Table 121: Pressure potential gradient (m m^{-1}) in the vadose zone from 0.25 m to 0.55 m and from 0.55 m to 0.85 m on 3 differently spaced sub-irrigation systems at West Sedgemoor (Note. positive values indicate downward flow and negative values denote upward flow).

	20 m spaced sub irrigation	
Date	**0.24 to 0.41m**	**0.41 to 0.81m**
18/02/2005	-0.82	-0.43
04/03/2005	-0.82	0.05
18/03/2005	-1.65	0.62
01/04/2005	-1.00	-0.67
15/04/2005	-0.82	0.62
29/04/2005	-1.82	0.48
13/05/2005	-4.12	0.86
27/05/2005	-1.82	-0.29
10/06/2005	-2.65	-0.48
24/06/2005	-7.06	-1.19
12/07/2005	-17.59	-0.33

Table 122: Pressure potential gradient (m m^{-1}) in the vadose zone from 0.24 m to 0.41 m on a 20 m spaced sub-surface drainage and irrigation system at Methwold Fen. (Note. positive values indicate downward flow and negative values upward flow).

I Future climate scenarios (2071-2100)

Year	Year	Obs' cum' rain	Obs' temp	Obs' cum' ET (2003/4)	Control cum' rain	Control temp	A2 cum' rain	A2 temp	A2 cum' ET	B2 cum' rain	B2 temp	B2 cum' ET
2071	1961	---	---	612	1092	11.3	904	15.0	748	1076	14.4	723
2072	1962	---	---	612	1348	10.5	1183	14.6	698	993	14.5	653
2073	1963	---	---	612	1108	11.3	907	15.4	764	1203	14.5	732
2074	1964	226	8.9	612	821	10.7	1021	14.9	649	1262	14.1	672
2075	1965	808	9.4	612	1164	11.5	1018	15.8	904	1259	13.1	588
2076	1966	875	10.1	612	1032	10.6	1024	14.7	702	871	14.4	760
2077	1967	791	10.0	612	960	10.3	1044	15.8	786	1085	15.2	808
2078	1968	715	9.8	612	1132	10.5	1003	15.3	821	1188	15.6	823
2079	1969	756	9.9	612	1161	11.0	852	14.1	740	1171	14.0	669
2080	1970	725	10.0	612	896	10.9	886	15.8	822	1017	15.0	733
2081	1971	693	10.1	612	900	10.8	1169	15.1	774	954	14.8	748
2082	1972	839	9.5	612	1152	10.3	952	15.1	856	791	14.3	721
2083	1973	646	9.9	612	946	10.8	1220	16.2	873	1217	13.9	617
2084	1974	891	10.0	612	1114	11.2	790	16.0	847	1072	15.1	796
2085	1975	609	10.4	612	1155	11.0	909	14.9	732	971	14.7	717
2086	1976	715	10.2	612	817	11.8	1005	15.9	772	893	14.7	769
2087	1977	760	10.0	612	883	11.5	1112	15.2	824	1183	13.8	611
2088	1978	700	9.8	612	801	11.4	1364	15.1	679	887	15.6	858
2089	1979	887	9.2	612	924	11.4	1162	14.9	691	1019	15.3	798
2090	1980	779	9.7	612	818	10.8	980	16.5	844	1132	14.3	601
2091	1981	728	9.8	612	1025	11.2	1121	15.5	749	1086	14.9	721
2092	1982	790	10.4	612	1232	11.6	830	15.2	751	1075	13.9	615
2093	1983	577	10.6	612	916	11.3	1066	15.8	844	1366	14.5	714
2094	1984	612	10.3	612	1004	11.0	1033	16.1	757	920	15.2	753
2095	1985	631	9.3	612	974	10.4	925	16.4	888	998	15.2	734
2096	1986	766	9.2	612	1039	11.7	788	17.1	897	897	14.9	684
2097	1987	620	9.6	612	949	11.6	1190	16.0	797	1099	15.1	699
2098	1988	668	10.2	612	1258	11.3	990	17.4	948	1028	16.2	862
2099	1989	740	11.1	612	1268	11.1	990	16.6	838	1124	17.1	913
2100	1990	614	11.2	612	1125	12.1	928	17.5	925	1287	15.4	675

Table 123: Annual observed (1961-1990) and modelled future climate scenario (2071-2100) for the South-West (West Sedgemoor).

Year	Year	Obs' cum' rain	Obs' temp	Obs' cum' ET (2003/4)	Control cum' rain	Control temp	A2 cum' rain	A2 temp	A2 cum' ET	B2 cum' rain	B2 temp	B2 cum' ET
2071	1961	538	10.4	639	942	10.3	885	14.2	702	902	13.5	693
2072	1962	471	8.7	639	1265	9.7	973	13.8	654	920	13.7	593
2073	1963	550	8.6	639	1026	10.5	924	14.4	681	1035	13.3	669
2074	1964	460	9.7	639	814	9.9	902	14.0	619	1127	13.3	638
2075	1965	595	9.2	639	1087	10.7	817	14.9	847	1123	12.0	523
2076	1966	607	9.8	639	942	9.6	904	13.7	632	794	13.5	707
2077	1967	591	10.0	639	926	9.6	1030	15.2	786	890	13.8	716

2078	1968	585	9.6	639	1045	9.7	839	14.4	769	1024	14.8	774
2079	1969	532	9.7	639	914	10.2	818	13.2	661	856	13.0	617
2080	1970	606	9.9	639	894	10.0	821	14.8	729	891	13.9	626
2081	1971	542	9.8	639	857	10.1	1129	14.0	687	850	13.9	692
2082	1972	403	9.6	639	949	9.5	789	14.1	779	889	13.1	620
2083	1973	351	9.9	639	918	10.3	1066	15.2	817	1150	13.0	534
2084	1974	628	9.9	639	1004	10.2	709	15.0	757	981	14.1	729
2085	1975	511	10.2	639	993	10.1	834	14.3	663	860	13.7	638
2086	1976	498	10.4	639	801	10.7	944	14.7	654	910	13.5	627
2087	1977	534	9.7	639	873	10.3	964	14.2	746	1120	12.8	552
2088	1978	556	9.6	639	743	10.5	1190	14.4	635	760.	14.4	758
2089	1979	628	9.2	639	865	10.9	1032	13.9	636	859	14.3	730
2090	1980	491	9.7	639	835	9.8	981	15.3	713	1006	13.4	562
2091	1981	570	9.5	639	931	10.5	1063	14.6	697	1100	14.0	679
2092	1982	686	10.1	639	1032	10.9	918	14.2	637	1023	12.9	540
2093	1983	580	10.4	639	855	10.6	934	14.9	771	1201	13.1	639
2094	1984	634	9.9	639	929	10.4	885	15.3	712	849	14.3	740
2095	1985	513	9.2	639	993	9.5	828	15.4	808	952	14.0	650
2096	1986	577	9.0	639	938	10.9	811	15.9	798	931	14.0	652
2097	1987	617	9.2	639	853	10.8	1030	14.8	718	1033	14.1	623
2098	1988	589	10.1	639	1132	10.3	829	16.5	885	977	14.9	787
2099	1989	518	11.2	639	1131	10.2	973	15.1	717	1013	15.8	807
2100	1990	407	11.3	639	904	11.3	799	16.6	864	1075	14.6	634

Table 124: Annual observed (1961-1990) and modelled future climate scenario (2071-2100) for East Anglia (Methwold Fen).

Location	Month	Observed (1961 -990)	Control	A2	B2
WSM	1	4.8	7.1	10.7	10.4
WSM	2	4.8	7.2	10.9	10.9
WSM	3	6.6	7.8	12.2	11.7
WSM	4	8.4	9.9	14.0	13.5
WSM	5	11.6	12.1	16.4	15.7
WSM	6	14.6	14.8	19.5	18.7
WSM	7	16.6	16.2	22.2	20.8
WSM	8	16.5	16.2	22.9	20.7
WSM	9	14.1	14.4	19.8	18.2
WSM	10	11.0	11.1	15.5	14.4
WSM	11	7.3	8.6	12.4	11.7
WSM	12	5.5	7.4	11.1	10.5

Table 125: West Sedgemoor monthly averaged actual and future climate scenario (2071-2100) temperature data.

Location	Month	Observed (1961 -1990)	Control	A2	B2
MF	1	3.9	---	9.2	8.8
MF	2	4.2	---	9.6	9.5
MF	3	6.4	---	11.5	10.5
MF	4	8.5	---	13.6	12.6
MF	5	11.8	---	16.1	15.0
MF	6	14.8	---	19.2	18.0
MF	7	16.9	---	21.5	20.4
MF	8	16.9	---	21.8	20.1
MF	9	14.4	---	18.8	17.5
MF	10	11.0	---	14.4	13.4
MF	11	6.8	---	10.9	10.4
MF	12	4.6	---	9.3	9.0

Table 126: Methwold Fen monthly averaged actual and future climate scenario (2071-2100) temperature data.

Location	Month	Observed (1961 -1990)	Control	A2	B2
WSM	1	4.8	7.1	10.7	10.4
WSM	2	4.8	7.2	10.9	10.9
WSM	3	6.6	7.8	12.2	11.7
WSM	4	8.4	9.9	14.0	13.5
WSM	5	11.6	12.1	16.4	15.7
WSM	6	14.6	14.8	19.5	18.7
WSM	7	16.6	16.2	22.2	20.8
WSM	8	16.5	16.2	22.9	20.7
WSM	9	14.1	14.4	19.8	18.2
WSM	10	11.0	11.1	15.5	14.4
WSM	11	7.3	8.6	12.4	11.7
WSM	12	5.5	7.4	11.1	10.5

Table 127: West Sedgemoor monthly averaged actual and future climate scenario (2071-2100) rainfall data.

Location	Month	Observed (1961 -1990)	Control	A2	B2
MF	1	45.2	---	126.7	117.7
MF	2	33.2	---	83.4	97.1
MF	3	39.2	---	64.4	83.5
MF	4	44.0	---	55.8	54.7
MF	5	44.8	---	53.7	62.9
MF	6	51.2	---	42.3	50.1
MF	7	44.5	---	35.9	47.9
MF	8	50.0	---	32.1	55.2
MF	9	49.4	---	57.6	67.1
MF	10	52.6	---	107.6	102.9
MF	11	52.6	---	127.8	112.2
MF	12	49.5	---	133.4	119.0

Table 128: Methwold Fen monthly averaged actual and future climate scenario (2071-2100) rainfall data.

Location	Month	Observed (2003&2004)	Control	A2	B2
WSM	1	1.1	---	0.5	0.5
WSM	2	1.4	---	0.9	0.9
WSM	3	2.4	---	1.7	1.7
WSM	4	4.0	---	2.7	2.6
WSM	5	5.1	---	3.5	3.2
WSM	6	6.4	---	4.0	3.8
WSM	7	5.7	---	4.3	3.7
WSM	8	5.8	---	3.9	3.1
WSM	9	3.8	---	2.5	2.2
WSM	10	2.5	---	1.2	1.2
WSM	11	1.1	---	0.6	0.6
WSM	12	0.8	---	0.4	0.4

Table 129: West Sedgemoor monthly averaged actual and future climate scenario (2071-2100) evapo-transpiration data.

Location	Month	Observed (2003&2004)	Control	A2	B2
MF	1	0.7	---	0.5	0.5
MF	2	1.2	---	0.8	0.8
MF	3	2.0	---	1.6	1.5
MF	4	3.4	---	2.6	2.4
MF	5	4.7	---	3.2	2.9
MF	6	6.6	---	3.6	3.4
MF	7	7.1	---	3.7	3.3
MF	8	6.9	---	3.3	2.7
MF	9	5.5	---	2.2	2.0
MF	10	2.2	---	1.2	1.2
MF	11	1.0	---	0.6	0.5
MF	12	0.7	---	0.4	0.3

Table 130: Methwold Fen monthly averaged actual and future climate scenario (2071-2100) evapo-transpiration data.

J SWAP-ANIMO mineralisation of organic matter

$$\text{Mean} \quad \rho_{dbd} = \frac{(0.44\times 0.13)+(0.17\times 0.56)+(0.10\times 4.67)}{(5.49\times 1000)} = 112.82\ \text{kg m}^{-3}$$

Equation 52: Averaged dry bulk density for West Sedgemoor peat soils.

$$\text{Mean} \quad \text{SOM} = \left[\frac{(0.39\times 0.13)+(0.60\times 0.55)+(0.69\times 4.67)}{(5.49)}\right]\times 100 = 66\,\%$$

Equation 53: Averaged soil organic matter content for West Sedgemoor peat soils

J.1 SOM mineralisation rates predicted for 2003 and 2004.

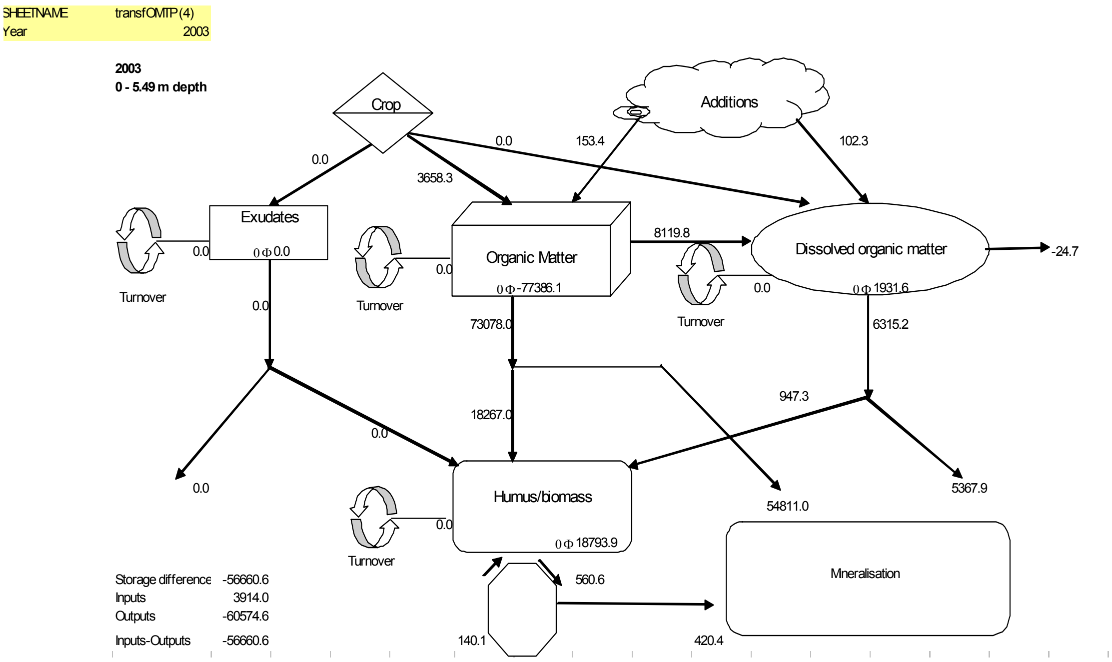

Figure 65: SWAP-ANIMO 2003 mineralisation output from West Sedgemoor fields with 100 m spaced ditches (Control).

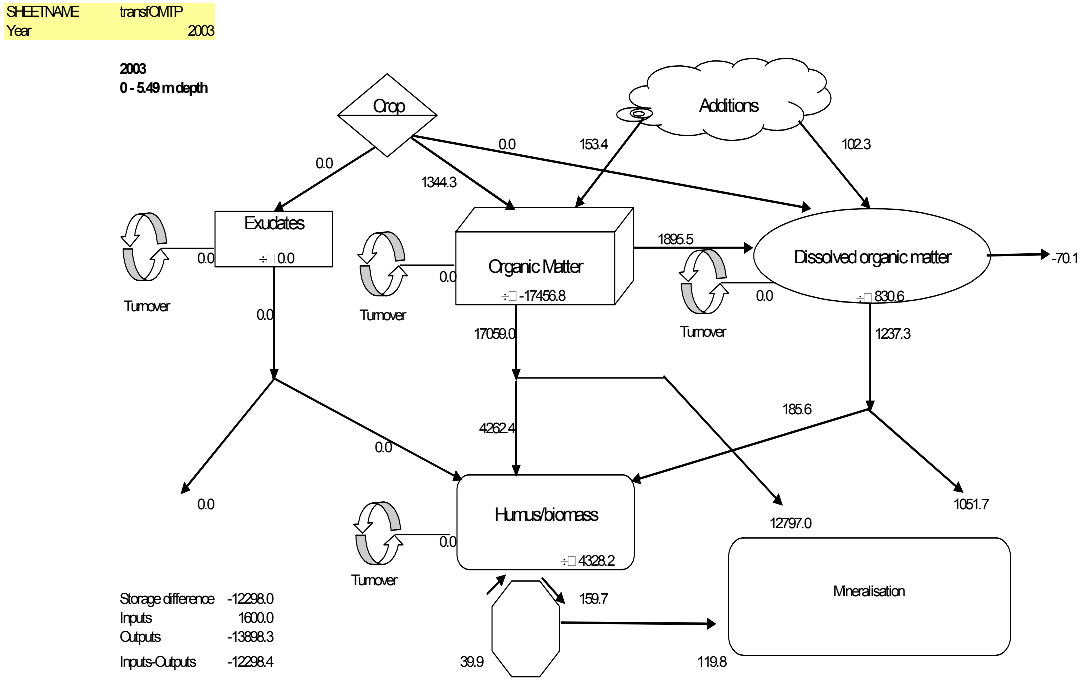

Figure 66: SWAP-ANIMO 2003 mineralisation output from West Sedgemoor fields with 10 m spaced sub-irrigation.

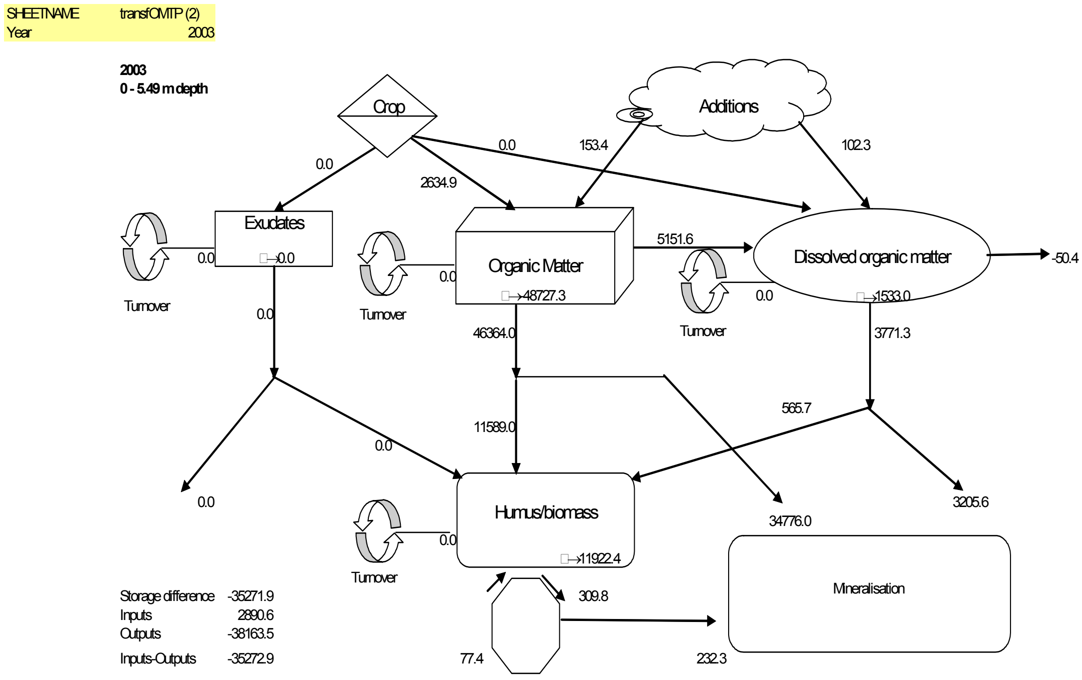

Figure 67: SWAP-ANIMO 2003 mineralisation output from West Sedgemoor fields with 25 m spaced sub-irrigation.

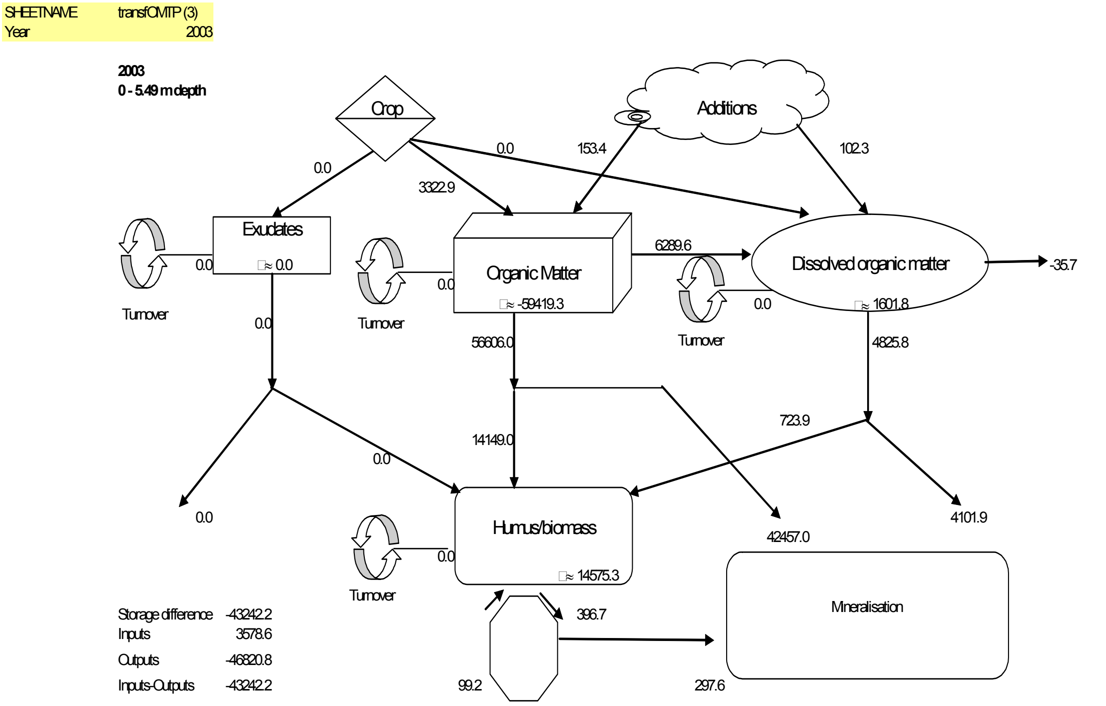

Figure 68: SWAP-ANIMO 2003 mineralisation output from West Sedgemoor fields with 40 m spaced sub-irrigation.

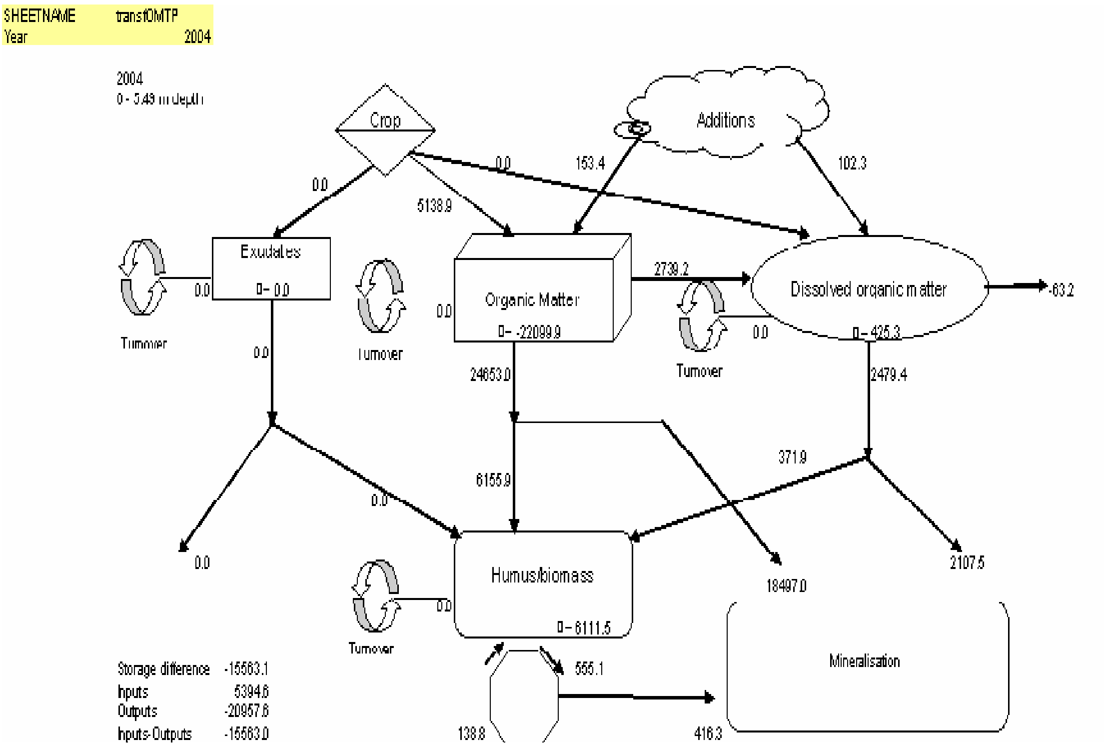

Figure 69: SWAP-ANIMO 2004 mineralisation output from West Sedgemoor fields with 100 m spaced ditches (Control).

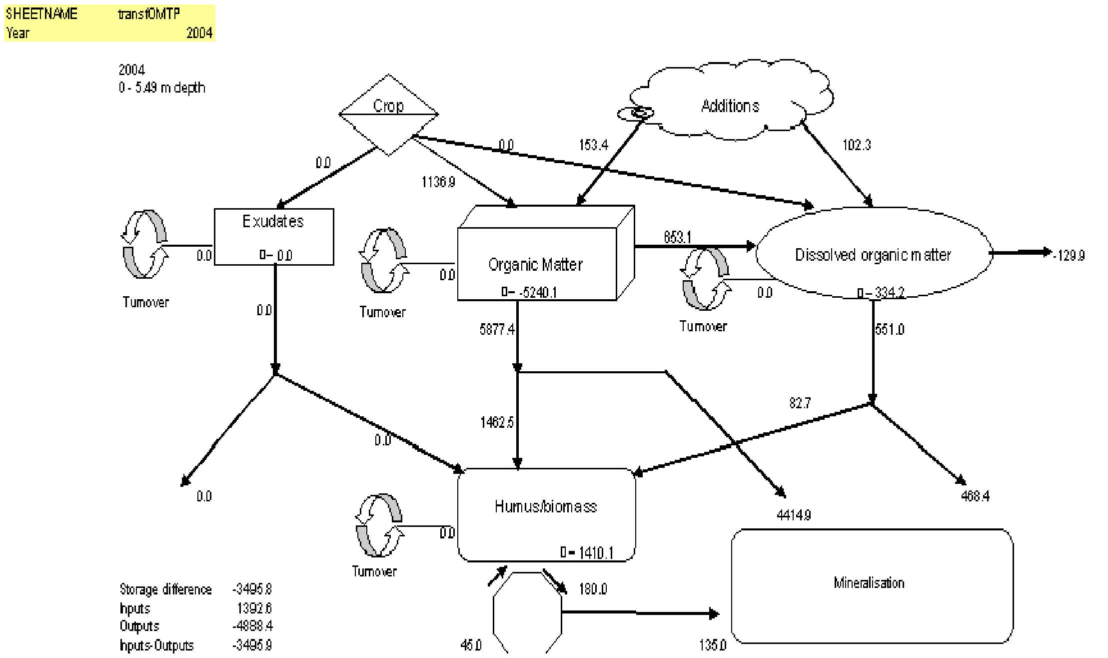

Figure 70: SWAP-ANIMO 2004 mineralisation output from West Sedgemoor fields with 10 m spaced sub-irrigation.

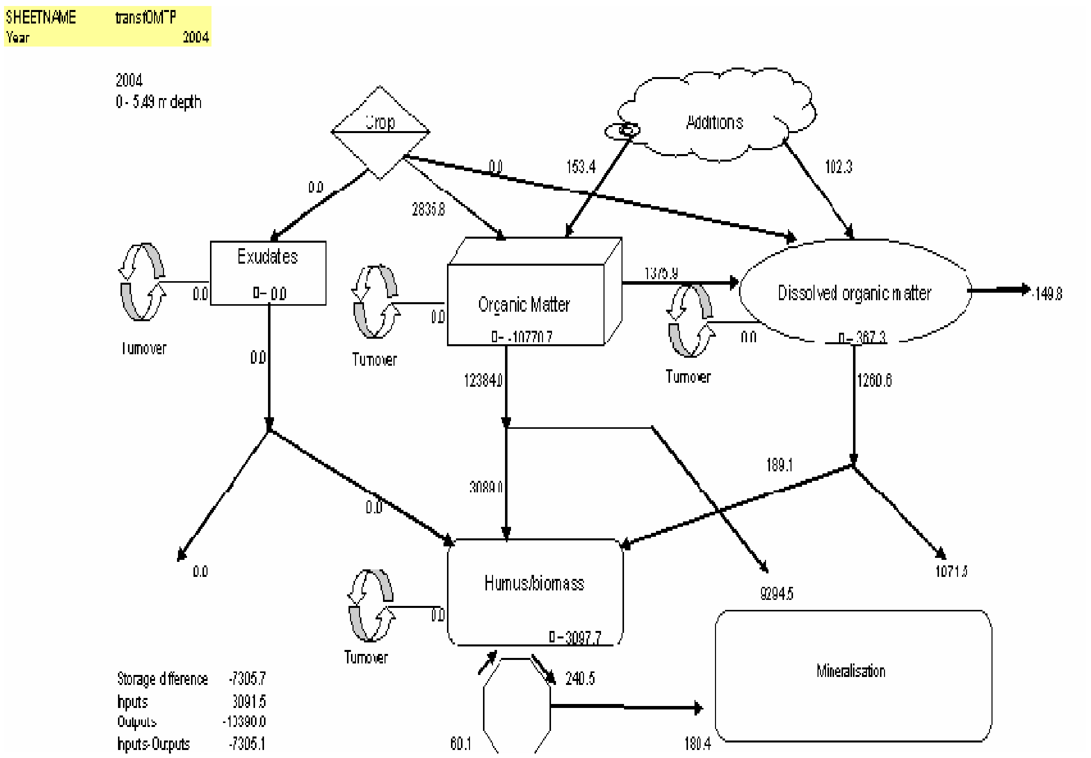

Figure 71: SWAP-ANIMO 2004 mineralisation output from West Sedgemoor fields with 25 m spaced sub-irrigation.

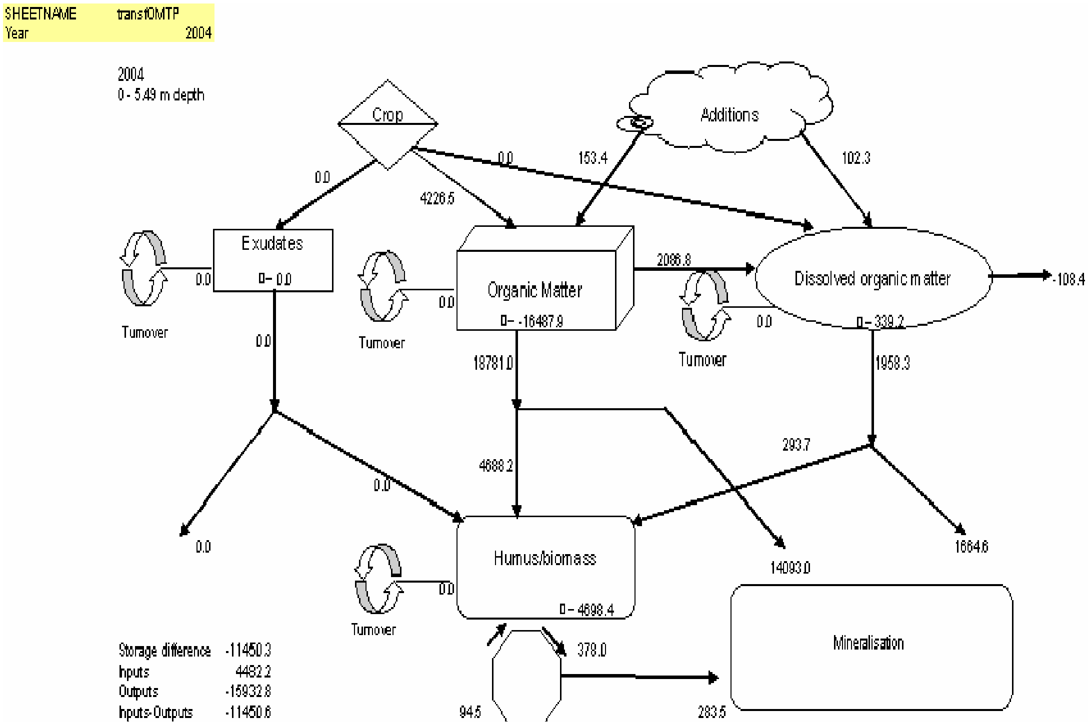

Figure 72: SWAP-ANIMO 2004 mineralisation output from West Sedgemoor fields with 40 m spaced sub-irrigation.

J.2 SOM mineralisation rate predictions for 2071 to 2100.

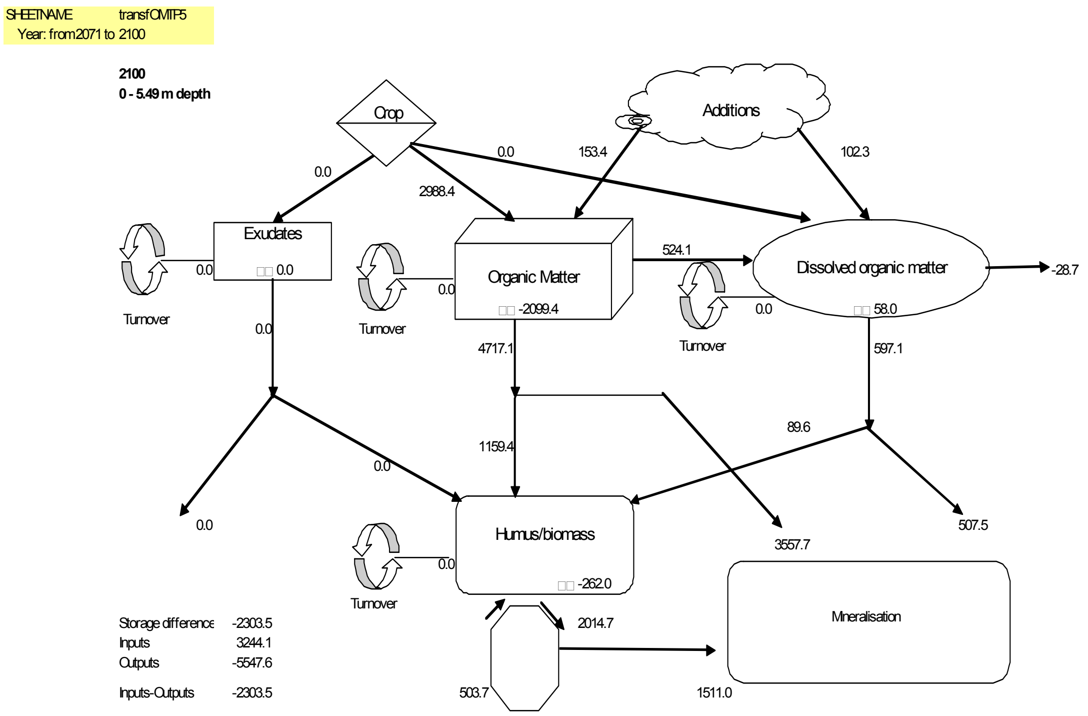

Figure 73: SWAP-ANIMO future scenario (2071-2100) of mineralisation output from West Sedgemoor fields with 10 m spaced sub-irrigation.

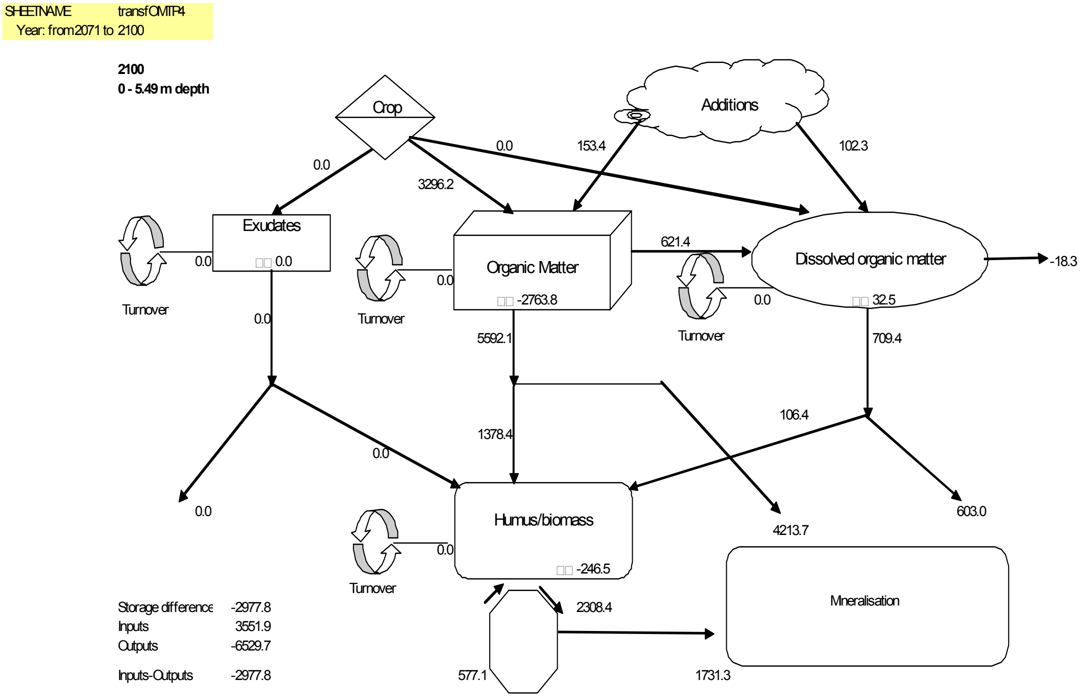

Figure 74: SWAP-ANIMO future scenario (2071-2100) of mineralisation output from West Sedgemoor fields with 25 m spaced sub-irrigation.

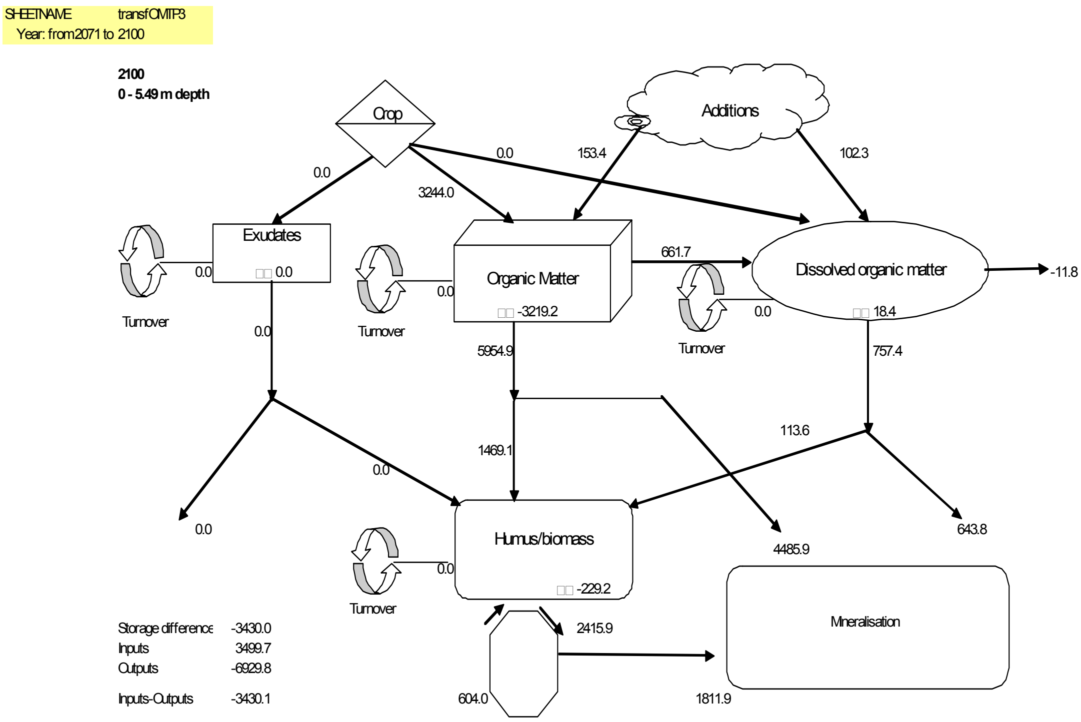

Figure 75: SWAP-ANIMO future scenario (2071-2100) of mineralisation output from West Sedgemoor fields with 40 m spaced sub-irrigation.

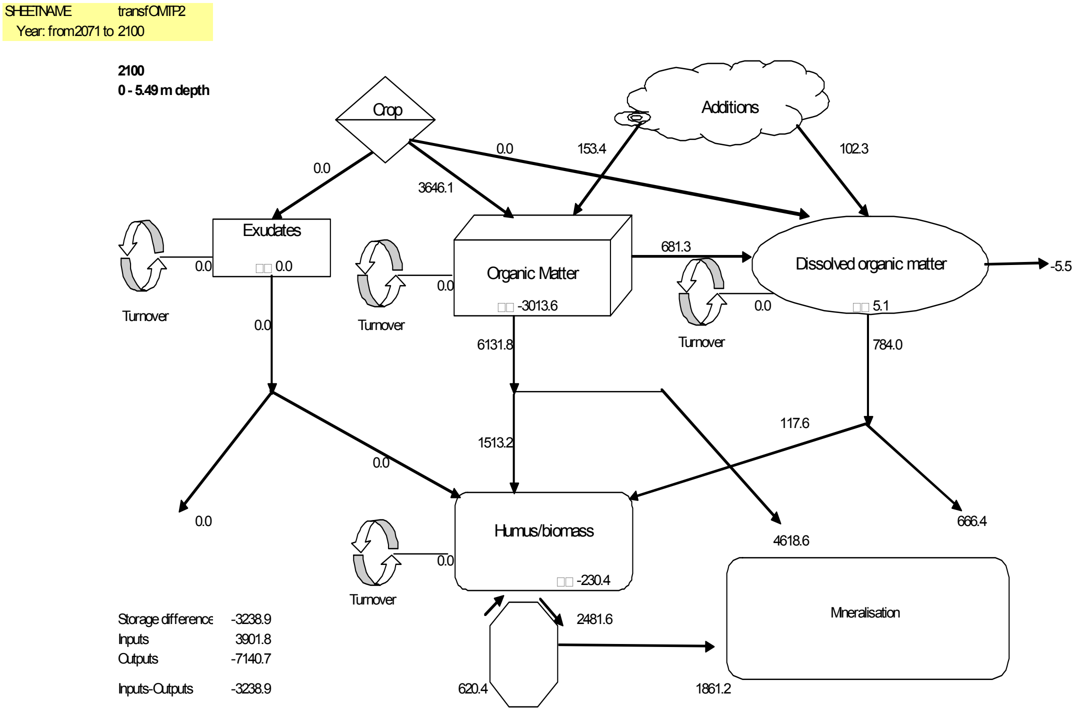

Figure 76: SWAP-ANIMO future scenario (2071-2100) of mineralisation output from West Sedgemoor fields with 100 m spaced sub-irrigation.

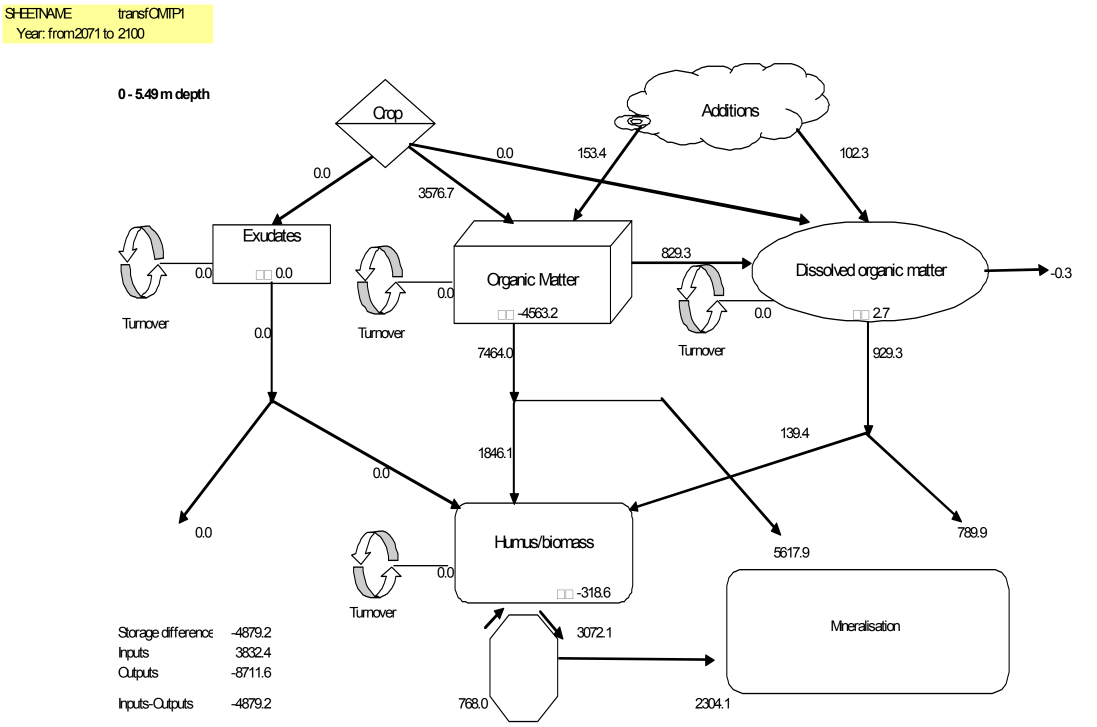

Figure 77: SWAP-ANIMO future scenario (2071-2100) of mineralisation output from West Sedgemoor 200m wide fields with no sub-irrigation.