

THE UNIVERSITY OF HULL

ENVIRONMENTAL PROCESSES WITHIN HEATHER MOORLAND

WITH PARTICULAR REFERENCE TO
THE EFFECTS OF CONTROLLED HEATHER BURNING
ON THE NORTH YORKSHIRE MOORS

being a Thesis submitted for the Degree of

DOCTOR OF PHILOSOPHY

in the University of Hull

by

MICHAEL A. FULLEN, B.Sc.

JANUARY 1981

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ACKNOWLEDGEMENTS

I gratefully acknowledge the help of the staff of the Department of Geography, University of Hull. Particular thanks are due to my Supervisor, Dr. R.R. Arnett. My thanks also go to Dr. S. Ellis, Dr. J.S. Pethick, Dr. K. Richards and Dr. R.C. Ward, and to the technical staff, particularly Mr. R. Dean, Mrs. P. Bell, Mr. B. Fisher, Mrs. J. Jackson, Mr. M. Marsh and Mr. K. Scurr.

I am indebted to the various people in other Departments who have allowed my trespasses. In particular I would like to thank Dr. D. Shaw for his constant guidance and Mr. S.F. Jafri for his technical assistance. Mr. J. Mitchell is due thanks for his help with liquid scintillation counting.

The assistance of many people concerned with the North Yorkshire Moors proved invaluable. I owe a special debt to Dr. R. Brown, of the North Yorkshire Moors National Park, whose constant advice and help was a great bonus. Thanks go to Mr. D. Smith for maintaining equipment on the Moors and Dr. J. Roberts, of the Institute of Hydrology, for his help. My thanks also go to the Forestry Commission and the Egton Estates Company for access to field sites.

Not least of all, I extend my thanks to the numerous people who braved the rigours of the upland humid environment to help in field work. These include G. Armitage, R. Aspinall, T. Caulfield, C. Dunn, S. Garnett, S. Gillman, J. Hoyle, J. Mangham, J. Milne and A. McDonald.

My thanks go to Mrs. A. Wilson for typing the Thesis.

This research was funded by a studentship from the Natural Environment Research Council.

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CHAPTER 1

INTRODUCTION

"The hills are shadows, and they flow from form to form, and nothing stands. They melt like mist, the solid lands. Like clouds they shape themselves and go."

A.L. Tennyson, 1864.

The transience of "The Everlasting Hills" (Linton, 1957) has been convincingly established by the current emphasis on process studies in geomorphology (Gregory and Walling, 1974). Measurement of denudational processes within the natural environment has afforded some understanding of rates of landform change (Douglas, 1967).

Geomorphologists are increasingly questioning the extent to which the hills "shape themselves and go". Man has a significant effect in influencing geomorphic processes, so much so that Brown (1970) argues that Man should be regarded as a "non-uniformitarian geomorphological process". Some argue that "anthropogeomorphology" should be recognized as a geomorphological discipline (Golumb and Eder, 1964; Fels, 1965).

"Man, the geomorphological process" (Brown, 1970) affects his environment in many ways. One manifestation of this influence is Man's usage of fire (Kozlowski and Ahlgren, 1974). Various writers present evidence that Man's usage of fire has affected the natural environment on a global scale. For instance, Motch (1970) presents evidence of the consequences of man-induced fires within Australian bushlands, while Van der Hammen (1974) discusses similar consequences within the Brazilian Shield. Sauer (1963) and Spence and Angus (1971) argue that fires have profoundly affected the

ecosystem of the North American prairies.

Both accidental and prescribed fires have had profound affects upon some of the upland regions of the British Isles. Particular attention has been paid to the dramatic consequences of accidental wildfires within moorland environments (Radley, 1965; McVean and Lockie, 1969; Doornkamp et al, 1980). However, fire is used as a land management technique within these areas. Several workers have postulated that prescribed controlled burning may be deleterious to the environment (Elliot, 1957; Gimingham, 1972). Lack of data and observations on the precise environmental consequences of prescribed burning prevents verification of these postulations.

Miller (1964) has described the aims of prescribed moorland burning, usually referred to as "muirburn". The superficial moorland vegetation cover, predominantly of heather (Calluna vulgaris), is burnt off on a 9 to 12 year rotation. Removal of the older heather stands allows regeneration of young heather seedlings. Renewed vigorous heather growth enhances the nutritional value of the crop to grazing sheep and grouse. Burnt patches are usually one to two acres in extent, thus the heather moorland landscape is often comprised of a mosaic of heather stands, in a variety of stages of growth.

This Thesis is a contribution towards our knowledge and understanding of the heather moorland environment. Before outlining the research programme, the literature on geomorphological, hydrological and pedological processes within the moorland environment are reviewed. Such a review should enable some of the main topics requiring further investigation to be identified. The review outlines current

knowledge on processes within the moorland environment and the ways these processes are altered by the removal of vegetation by burning. Lack of information on a number of processes necessitates some theorisation on how the natural system will be changed by burning and some reliance on research which does not directly pertain to the moorland environment.

BURNING AND ENVIRONMENTAL RESPONSE

Most information on the environmental response to vegetation removal by burning has been forthcoming from a number of studies within semi-arid lands. One of the earliest scientific investigations was by Hoyt and Troxel (1932). The accidental burning of large areas of Fish Creek catchment, southern California, caused a large increase in water and sediment discharge from the Catchment. Mean annual discharge over the six years after the fire increased to 475% of pre-burn discharge.

A number of similar studies have described increases in erosion consequent upon burning. These are usually experimental catchments which have experienced accidental fires. The San Dimas fire of 1960 devastated 500 acres of the 1500 acre catchment, resulting in increases in sediment loss by a factor of 2 to 35 and increases in runoff by factors of 200 to 800 (Hopkins et al, 1961; Grouse and Hill, 1962; Corbett and Green, 1965).

Similar fires have verified the San Dimas results. The burning of the Boulder Mountain catchment, Arizona in 1959 (Pase and Ingebo, 1965), Rocky Mountain catchment, Arizona in 1957 (Rich, 1962) and the Tumut Valley, New South Wales in 1970 (Brown, 1972) produced similar consequences.

Removal of the vegetation effected large increases in sediment and water loss from the catchments.

Within humid temperate lands the environmental consequences of vegetation removal appear to be different in degree, but not kind. The defoliation of part of Hubbard Brook catchment, New Hampshire, USA, led to increases in mean runoff of 40%, 28% and 26% over the subsequent three years. Sediment loss was also increased (Hornbeck et al, 1970; Hobbie and Likens, 1973).

The environmental adjustments noted above bear some relevance to the moorland environment. Available literature suggests that the presence of heather cover protects the underlying soil from erosion (Arnett, 1977; Finlayson, 1977). When the vegetation is removed by burning the nature of processes acting upon the soil surface are changed, and the burnt moorland environment is much more susceptible to erosion.

Stocker (1923) observed that the removal of heather induced a number of microclimatic changes upon the Bremerhaven heaths. Delaney (1953) and Barclay-Estrup (1971) regard the heather cover as a buffering system, protecting the underlying soil from extremes of temperature. Removal of the vegetation allows greater variability in temperature.

Of particular geomorphological importance is the enhancement of nival processes by vegetation removal. Soons and Rainer (1968) and Gradwell (1957) have described the efficacy of nival processes in accentuating surface removal, within the Southern Alps of New Zealand. Within the moorland environment Radley (1962) suggests that nival processes encourage the

disintegration of peat surfaces within the Peak District. Consequently, the peat is more crumbly and friable and so more susceptible to erosion. Within the North York Moors Arnett (1977) has stressed the importance of needle-ice or "pipkrake" formation in creating soil instability.

The heather canopy is very effective in retaining and conserving moisture (Leyton, 1955). Gimingham (1964) reports that relative humidity under the heather canopy is frequently higher than 80% and may exceed 95%. Thus, the heather microclimate is cool and moist (Delaney, 1953).

Removal of the heather cover by burning allows greater variations in moisture conditions. The soil surface is then more liable to rapid wetting and drying, accelerating the formation of desiccation cracks and soil instability (Knighton, 1974; Harvey, 1974).

A heather cover protects the underlying soil from the potentially erosive effects of wind by decreasing surface velocities (Gimingham, 1964; Barclay-Estrup, 1971). However, the wind's erosive potential is often realised when the vegetation cover has been removed. Imeson (1971) provides evidence for increased wind erosion on burnt areas within Bransdale, North York Moors, which collaborates with evidence from the heaths of the Veluwe, Netherlands (Stoutjesdijk, 1959).

The presence or absence of vegetation fundamentally affects the movement of water and sediment through the moorland environment. Raindrop impact tends to encourage the movement of surface material (Ellison, 1945, 1950; De Ploey, 1967). However, vegetation protects the surface from the erosive effects of

raindrop impact. The effect is explained by Morgan (1979) who maintains that

"... the main role of vegetation is in the interception of raindrops, so that their kinetic energy is dissipated by the plant rather than imparted to the soil."

Within heather moors raindrop impact will tend to be absorbed by the vegetation, but when the heather is absent raindrops may impart their energy directly to the soil surface, encouraging the dislodging and movement of soil particles. This disintegration of soil crumbs might further result in the sealing of the surface soil layer with clay and so encourage greater runoff (Young, 1972).

Vegetation removal may alter hydrological processes in a number of ways. Aranda and Coutts (1963) and Barclay-Estrup (1971) report that heather has the ability to intercept large amounts of rainfall. Furthermore, transpiration rates from heather stands may be in excess of $20 \text{ t ha}^{-1} \text{ day}^{-1}$ (J. Roberts, pers. comm). Removal of the vegetation cover will diminish the importance of these hydrological transfers and increase runoff volumes. Within experimental plots Arnett (1979) found runoff to be some 16 times greater on burnt ground than ground with a mature heather cover.

The greater propensity for burnt areas to generate runoff will encourage greater sediment loss. This loss will be accentuated by the absence of vegetation impeding the movement of sediments through the moorland environment. Thus, Arnett (1979) found that sediment loss was some 20 times greater on the burnt runoff plot than on the vegetated runoff plot.

Several components of sediment discharge from the moorland environment may be recognized. The nature and types of sediment

lost from the moors may vary in response to moorland burning. Sediments may be in the particulate or solutional phase, each containing organic or inorganic components. Furthermore, particulate sediments may be transported as suspended load or bedload.

Available data suggests that the largest component of sediment loss from the moorland environment is in the solutional phase (Oxley, 1974; Burgess, 1976; Arnett, 1977; Finlayson, 1977).

The dynamics of solute movement is little understood. Even less is known on the response of solutes to vegetation removal by burning. Crisp (1966) reports an increase in solute loss due to peat erosion, within Roughsike catchment, Westmorland. Peat erosion is a plausible consequence of vegetation removal. Thus, one might postulate an increase in solute loss following moorland burning. There is considerable evidence that solute loss and pedological processes within heather moorland are closely inter-related (Allen, 1964). Consequently this theme will be examined more closely in the discussion on pedological processes.

Dissolved organic matter contributes a relatively small component of dissolved sediments within the North York Moors (Arnett, 1978). Evidence from a variety of fluvial environments confirms this assertion (Hobbie and Likens, 1973; Brinson, 1976). The release of dissolved organic matter is probably related to biogenic processes, in particular the secretion of chelates, such as fulvic and humic acids, from heather litter (Grubb and Suter, 1971; Robinson, 1971). However, little is known of the response of these biogenic processes to moorland burning. Loss of particulate organic matter from the moorland environment is of some significance. Particulate organic matter formed some 20% to 40% of suspended sediment discharge within 16 catchments in the North

York Moors (Arnett, 1978). Jackson (1975) differentiates between allochthonous and autochthonous organic sediments. Allochthonous organic sediments are those introduced into stream water from the adjacent catchment area. Arnett (1978) stresses the importance of physically eroded clastic sediments within the clay-humus complex in contributing to organic sediment loss. Others emphasise the importance of organic plant debris flushed into streams during storm events (Nelson and Scott, 1962; Brinson, 1976). Autochthonous organic matter is that portion endemic to the stream ecosystem and within moorland streams is composed of a variety of living and dead components (Egglisshaw and Shackley, 1971).

Considering the complexity and variety of organic sources within moorland environments knowledge of the response of these sources to vegetation disturbance is sparse. The literature does provide evidence of a positive relationship between discharge and organic sediment loss (Fisher, 1970; Hobbie and Likens, 1973; Finlayson, 1978). Since increased runoff is a possible consequence of vegetation removal, then one might postulate an increase in organic denudation consequent upon burning. However, Hobbie and Likens (1973) emphasise that organic matter appears to have a buffering capability, so that it does not necessarily directly respond to prevailing environmental conditions. Thus, the defoliation of Hubbard Brook only resulted in a slight increase in organic sediment loss (Hobbie and Likens, 1973).

Suspended mineral sediment load released from moorland environments appears to be positively related to stream discharge (Oxley, 1974; Burgess, 1976; Finlayson, 1978). Arnett (1978) suggests that mineral sediments tend to be transported at high discharges, due to the increased competence of streams to entrain and transport

the relatively dense mineral sediments. Theoretically, the increased runoff from burnt areas will encourage an enhanced capacity to transport mineral sediments.

Little data is available on bedload transport within Calluna moorland. Within the heather-covered catchment of East Twin Brook, Somerset, Finlayson (1977) reports little bedload transport. A heath fire within Lyn Bychan catchment, North Wales, resulted in an increased sedimentation rate within the lake (Rummary et al, 1979). Thus, an increase in bedload transport is a plausible consequence of moorland burning.

Despite the importance of management regimes within moorland environments, few studies have attempted to investigate the precise effect of these practises. A number of studies have concentrated upon the dramatic consequences of accidental fires (Radley, 1965; McVean and Lockie, 1969). Several writers have commented upon the effects of prescribed burning. Imeson (1971) reports the second highest catchment denudation rate within the British Isles for Bransdale catchment, North York Moors. Estimated denudation of suspended sediments was $534.0 \text{ t/Km}^2/\text{yr}$. for the sub-catchment of Upper Hodge Beck. The only reported value within the British Isles which is higher is that for exposed gullies in the Howgill Fells, Cumbria (Harvey, 1974). Imeson concludes that

"... the moorland area is losing a tremendous amount of sediment and most of the material is derived from recently burnt areas."

Much lower values of sediment loss from Upper Hodge Beck have been reported by Burgess (1976) who estimates denudation of the catchment at $61.9 \text{ t/Km}^2/\text{yr}$. Burgess is more uncertain about the

effects of moorland burning and concludes

"... little is known of the effects of moorland burning."

Several studies suggest that the burnt moorland environment is in a state of greater erodibility than vegetated moorland. Soil instability and movement within Levisham Moor, North York Moors, has been correlated with burning practises over the past 200 years (Curtis, 1975). More recently, Arnett (1978) reports greater runoff and sediment yield from burnt runoff plots compared with heather covered plot. However, various uncertainties on ~~geomorphological and hydrological processes~~ within the Calluna moorlands remain.

A number of questions exist concerning pedological processes within the moorland environment and the ways in which they are altered by moorland burning. While a number of studies have examined processes within undisturbed moorland soils, few have investigated changes in soil properties due to burning. The major focus of attention on pedological processes within moorland soils has been concerned with the pathways of nutrients through the Callunetum ecosystem. In the subsequent review the nature of physical pedological processes are examined. Due to lack of information on these processes, some reliance is placed upon investigations in other environments. The discussion is concluded with a review of literature concerned with the nutrient status of heather moorland.

Processes acting upon the surface litter layer (L) of moorland soils appear quite different on heather covered soils compared with soils where the vegetation has been removed. Imeson (1971)

reports a net accumulation of heather litter beneath mature heather stands in Bransdale. Such accumulation is related to the autumnal release of litter by the Calluna plant (Robertson and Davies, 1965). In contrast, Imeson reports a net loss of litter from burnt areas. Litter was removed both by wind and by the headward extension of gully systems on to recently burnt areas.

Pedological processes within undisturbed moorland soils are usually associated with the podzolisation of the soil. Dimbleby (1962) and more recently Cundill (1971) and Tinsley (1975) regard the present heather cover of many moorland areas as the combined product of man's interference and climatic change. They argue that over-grazing and burning have encouraged ecosystem degeneration, from woodlands with brown earth soils during neolithic times, to the present situation of Calluna heathland and peaty, gleyed podzolic soils.

A number of writers have examined the nature of the podzolisation process (Grubb et al, 1968; Grubb and Suter, 1971; Robinson, 1971). Chelates secreted from heather litter act as sesquioxides translocating material within the soil. Under the dominant leaching conditions mobilisation of material encourages podzolisation and iron-pan formation. The development of an impermeable pan within the soil profile encourages saturation of the profile. Gleying and anaerobic conditions associated with peat formation may ensue.

Evidence on how these processes are altered is sparse, although reports from forest fires in the United States suggest that burning has a deleterious effect upon soil characteristics. Numerous forest studies have been reviewed by Ahlgren and Ahlgren

(1960) and Taber and Murphy (1971). Fowells and Stevenson (1934) report that a forest fire leads to considerable losses of organic matter, a point supported by Austin and Baisinger (1955). The latter also referred to a lack of moisture-holding capacity within burnt soils. Suman and Halls (1955) noted that burnt soils were more susceptible to compaction by grazing animals.

The extent to which these studies may be transposed to a moorland environment is uncertain. However, the lack of data on the ways in which these various soil characteristics are altered by burning invites investigation. Maltby (pers. comm.) reports considerable changes within intensively burnt areas on Glaisdale, North York Moors, where burning has stimulated the growth of soil microflora and bacteria populations. Such an increase encourages the respiration and oxidation of organic substrates. Hence, the anaerobic conditions which helped to create the extensive blanket peats of Glaisdale are now being reversed by aerobic processes. Thus, there is evidence that burning is significantly altering pedological processes within the moorland environment.

Burning may alter the magnetic properties of soils. The process has been described by Longworth et al (1979). Oxidation by burning encourages the formation of ferric oxides or the conversion of ferric oxides from non-magnetic or anti-ferromagnetic forms into strongly ferrimagnetic forms.

In field investigations, Longworth et al (1979) found a two-fold increase in the magnetic susceptibility of topsoil samples, within the Caldby Hill area, Lancashire, and this increase was attributed to the effects of a heath fire. Similarly, Bloemendal et al (1979) report a peak in the magnetic susceptibility of lake

sediments within Llyn Goddionduon catchment, North Wales, correlated with the deposition of sediments from a 1951 forest fire. Further confirmation of such an alteration has come from Rummery et al (1979). Sediments deposited consequent to a heath fire had magnetic susceptibilities 20-fold greater than the surrounding sediments, within Lyn Bryan catchment, North Wales.

While scant attention has been paid to physical changes in soil properties due to moorland burning, several writers have commented upon the nutrient status of moorland soils. Within the undisturbed heather environment nutrients are maintained in a steady-state equilibrium within the soil-vegetation system (Allen, 1964; Chapman, 1967). The burning of heather introduces a great deal of disturbance to the steady-state system.

Burning converts biochemical compounds within the biomass into a variety of forms. Slash fires tend to release carbon monoxide, carbon dioxide, nitrogen oxides and hydrocarbons (Murphy, 1970). Allen (1964) broke down the smoke constituents of laboratory simulated heath fires into aqueous condensate, tar and suspended matter. Large proportions of the elements previously retained within the biomass may be contained in the smoke constituents.

Losses of nitrogen are particularly high during heath fires.

Allen (1964) suggests that over 50% of nitrogen within the biomass may be driven off in smoke. Chapman (1967) places loss as high as 95% with 45 Kg ha⁻¹ of nitrogen being lost from one heathland fire on the South Downs. High losses of carbon and sulphur were reported for these burns.

Base elements are also liberated by fire. Allen (1964) reports

losses, varying from 1.4% to 4.9%, 0.4% to 2.1% and 0.1% to 2.4%, of potassium, magnesium and calcium, respectively. Nutrient loss was positively related to the intensity of burning. Chapman (1967) reports losses of these elements to be as high as 20%.

Some of the volatilised nutrients may be returned to the Callunetum ecosystem, as over large tracts of heather, nutrient losses from one burnt patch may become inputs to another, as the smoke settled, so overall nutrient loss may be small. However, on small heathland areas such losses may be greater, as the smoke is transported beyond the Callunetum ecosystem. Thus, Chapman (1967) considers that the burning of the small heather areas of the South Downs is leading to a depletion of nutrients within the ecosystem.

Nutrient inputs to burnt moorland are primarily from atmospheric sources. These sources include salts in precipitation and dry atmospheric fallout. Atmospheric nutrient input is variable. Some workers argue that nutrient input is dependent on distance from marine sources (Junge and Werby, 1958; Cryer, 1976) while others emphasize the importance of industrial sources (Stevenson, 1968).

Independently, Allen (1964) and Chapman (1967) calculated that atmospheric nutrient inputs over a number of years, equalled any losses due to burning, except for nitrogen and phosphorus.

However, some debate surrounds the question of whether atmospheric sources of nutrients are sufficient to make good losses due to burning. Miller (1964) recognizes two schools of thought. Some regard the income of nutrients, largely from atmospheric sources, to counter-balance nutrient loss from burning, thus maintaining the ecosystem in steady-state equilibrium (Boggie et al, 1958;

Grant et al, 1963). Others regard atmospheric input to be insufficient to maintain steady-state equilibrium (Elliot, 1957; Kenworthy, 1964; Gimingham, 1975).

Gimingham (1975) argues that the nutrient cycling model is very much a black box model. Although nutrient input may be sufficient overall, not all nutrients will be taken up by the soil-vegetation system. Nutrients entering the system will themselves be liable to removal by leaching or runoff. Hence, uncertainties remain concerning the pathways of nutrients through the Callunetum ecosystem.

Disturbance to nutrient cycling by heather burning may effect soil reaction. The liberalisation and volatisation of relatively alkaline soluble salts encourages a decrease in soil acidity. Such a process has been recognized in a variety of burnt environments, including burnt gorselands in New Zealand (Miller et al, 1955), burnt heathlands of the Fenno-Scandinavian shield (Viro, 1974), burnt forest soils in Zambia (Trapnell et al, 1976) and burnt forest soils in the United States (Fowells and Stevenson, 1934; Austin and Baisinger, 1955).

In laboratory simulations of heather fires Allen (1964) found that the elements K, Ca, Mg and P within the biomass were converted into the soluble salts KCl , $CaCl_2 \cdot 6H_2O$, $MgSO_4 \cdot 7H_2O$ and Na_2HPO_4 respectively. The presence of relatively alkaline salts on or within the acidic humus layer would tend to neutralise acids within the humus. Consequently soil pH may increase.

Field investigations confirm an increase in soil pH consequent upon moorland burning (Elliot, 1957). Allen (1964) reports an

increase in soil pH from 4.4 to 5.2 within the uppermost 1 cm of burnt soils. Within Glaisdale, Mellor (1978) found soil pH on undisturbed moorland to be in the range 3.1 to 3.4, while "badly burnt" soils had pH values in the range 4.15 to 4.25. Hence, soil reaction changes may be considered a possible surrogate for changing soil nutrient status.

Increases in soil nutrient status may only be temporary as leaching tends to translocate soluble salts deeper into the soil profile. Heather is a very shallow rooted plant (Rennie, 1957; Boggie et al, 1958; Chapman, 1970; Gimingham, 1972). Consequently, leaching may remove these salts from the biogeochemical cycling of the Callunetum ecosystem.

The effectiveness of leaching processes are influenced by the nature of soil cover. Allen (1964) suggests that soils with a thick surface organic layer are effective in retaining liberated salts. However if the organic layer is absent, or if the salts are translocated to a sandy substrate, leaching may proceed at a greater rate.

Overland flow could more rapidly remove salts from the moorland environment. The pathways by which salts are translocated could have some bearing on the solute dynamics of moorland streams. Removal by overland flow could rapidly flush the salts into streams, while translocation within the soil profile would encourage a longer, slower release of salts within interflow. Such processes could affect both the solute content of moorland streams and the duration of solute level disturbance induced by burning. However, lack of field investigation precludes further elaboration upon these processes.

Geomorphological, hydrological and pedological processes within the moorland environment are complex, and in many aspects, little understood. The preceding review enabled the identification of a number of themes which merit further investigation. Before these themes are discussed, the regional context of the research programme should be outlined. Hence, in the next section, some of the main attributes and characteristics of the moorland environment, in particular those of the North Yorkshire Moors, are described.

THE NORTH YORKSHIRE MOORS : THE REGIONAL SETTING

The structure of the North Yorkshire Moors is dominated by the Cleveland dome, one of a series of elongated upfolds and basins resulting from tertiary folding of the area (Hemingway, 1958). The upland massif is bounded by vales filled with Quaternary deposits to the north, south and west, and by the sea in the east.

The valleys and moors of the region vary in altitude between 120 and 460 m O.D., while the areal extent of the region, as defined by the National Park boundary, is some 1430 Km² (Fig.1).

Geologically the Moors are part of the Jurassic system deposited 135 to 180 million years B.P. The Deltaic Series, composed of sandstones, shales and impure limestones, are most extensive on the upland planation surface (De Boer, 1974). Some of the older strata have been exposed as a series of concentric inliers, particularly in the valleys crossing the southern limb of the Cleveland anticline.

The drainage pattern consists of both east-west and north-south flowing river networks. The principal divide between the two systems is the Central Watershed (Cundill, 1971), separating to

the north, the east-flowing River Esk, while to the south a series of smaller, parallel drainage basins drain into the Vale of Pickering.

The climatic regime is of a cool temperate oceanic type. Annual rainfall increases with altitude from about 650 mm on the coast to over 1050 mm in the upland areas of Farndale. Precipitation is distributed throughout the year, frequently falling as snow in winter. Burgess (1976) reports that on average snow is lying for 20 to 25 days per year.

Temperatures are generally cool, but variable, throughout the year. Mean monthly values recorded at Silpho Moor climatic observatory (G.R. 957946) over the year 1971-72 ranged from 2.5°C in January to 13.8°C in August.

Soil types, to some extent, reflect lithological variations. On the calcareous outcrops to the south Rendzinas and Brown Earths are frequent. On the upland surface podzolised acid soils frequently lie above gritstones, giving way to peaty gleys where drainage is impeded, above shales. The complex relationships of lithology and drainage are reflected in the highly variable nature of the upland soils (Bendelow and Carroll, 1976).

Climatic, edaphic and anthropogenic factors have influenced the vegetation of the Moors. On the upland areas heather (Calluna vulgaris) dominates the 518 Km² area classified as "open land", which accounts for some 36% of the area of the National Park (National Park Committee, 1980).

The upland plateaux supports a variety of other plant communities. On the drier plateau areas crowberry (Empetrum nigrum), bilberry (Vaccinium myrtillus) and common bent grass (Agrostis tenuis) are

common. In moister areas these associations usually give way to communities of cross leaved heath (Erica tetralix), heath rush (Juncus squarrosus) and flushes, such as soft rush (Juncus effusus) and bog moss (Sphagnum spp). On drier moorland slopes braken (Pteridium aquilinum) and wavy hair grass (Deschampsia flexuosa) are more frequent.

Tracts of coniferous plantations are distributed throughout the upland plateaux. In terms of acreages these are composed predominantly of Scots pine (Pinus sylvestris) and Sitka spruce (Picea sitchensis). The areal extent of these plantations, particularly towards the south and east of the Moors, is expanding due to afforestation programmes (Eyre and Palmer, 1973).

The alluvial and colluvial soils of the dales and valley sides are predominantly permanent grassland areas. On the richer calcareous soils to the south arable activities are more evident.

THE RESEARCH PROGRAMME

A number of themes examined within the previous section attracted investigation. Research formed an integral part of a broader research effort involving long-term programmes within the Department of Geography, University of Hull, and with the Moorland Research Programme (Countryside Commission, 1977; North York Moors National Park Committee, 1980), initiated after the extensive moorland fires of 1976. Within this programme various research workers and institutions studied the Moors with a view to developing a scientific understanding of this particular environment. Hopefully, such research will enable practical solutions to some of the ecological problems of upland areas.

Discussion on the adjustment of natural systems to Man's interference is often hindered by lack of knowledge on conditions prior to the disturbance (Douglas, 1967). Thus, processes within the moorland environment require careful monitoring and evaluation before the effects of the disturbance can be assessed. Consequently, much of the research was devoted to a study of natural processes within undisturbed heather moorland.

Processes were monitored within the framework of a drainage basin, described by Chorley (1975) as the "fundamental geomorphic unit". A study of processes within the drainage basin context allows the examination of the complex interaction of inputs, throughputs and outputs of energy and matter through the catchment system (Gregory and Walling, 1971).

The small "experimental" catchment (Toebes and Ouryvaev, 1970) selected possessed an almost complete cover of heather, thereby affording a field site for the evaluation and quantification of hydrological and geomorphological processes within undisturbed heather moorland. The calibration of "control" conditions facilitated an examination of catchment response to vegetation removal by burning (C. Dunn, pers. comm.). Thus, the catchment study forms a contribution to a longer term programme of research into the moorland environment.

Further control over field investigation is facilitated by reducing the scale of enquiry. Consequently, ancillary experiments into geomorphological, hydrological and pedological processes within both vegetated and burnt moorland were conducted within smaller field sites.

The investigation of soil plots allowed the acquisition of data on pedological processes within heather moorland, in particular the disturbance introduced by moorland burning. One soil plot remained vegetated, as a control, while two adjacent ones had their vegetation removed by burning. As the intensity of the two burns varied, the experiment allowed enquiry into the environmental changes induced by burning and the effect of two different intensities of burn upon soil properties. Instrumentation monitoring surface micro-processes was integrated within the framework of the experimental plots.

~~Further clarification of surface micro-processes on disturbed and~~
undisturbed moorland was forthcoming from another series of plot studies. The literature does suggest that the soil surface of burnt moorland is more susceptible to erosion and more potentially mobile. However, little data have been collected on soil surface mobility, hence soil movement on vegetated and burnt moorland was investigated. As a means of measuring movement soils were labelled with a radioactive isotope. The soil diffusion experiments were conducted within runoff plots, thus enabling the collection of data on water quality and quantity from both vegetated and burnt moorland.

To summarize, field investigations were on three scales of enquiry. Catchment conditions within a heather-covered catchment were monitored, as part of a long-term research programme. At successively smaller scales of enquiry, soil characteristics and surface micro-processes were investigated on both burnt and unburnt heather moorland. The remainder of this Thesis is devoted to the methods of enquiry, and analysis of the results from these field investigations.

In the next three chapters the methods of field enquiry and data collection are discussed. Chapter 2 outlines the catchment study. Chapters 3 and 4 discuss the experimental design and progress of the soil plot and soil diffusion experiments, respectively. Chapter 5 is concerned with the laboratory and statistical techniques whereby field samples and data were analysed.

The second part of the Thesis is an analysis and discussion of the results of field investigation. Chapters 6 and 7 analyse the salient characteristics of the hydrology and denudation of the catchment, respectively. In Chapters 8 and 9 the results of the soil plot experiments are discussed. Chapter 10 examines the results of soil diffusion experiments.

The Thesis is concluded by Chapter 11. Results and analyses from the three scales of enquiry are collated and compared. The contributions made by the study to existing knowledge are identified and recommendations for further research are made.

CHAPTER 2

THE CATCHMENT STUDY

The aim of the catchment study was to investigate geomorphological processes within the Calluna moorland environment. Particular attention was focussed upon the characteristics and magnitude of sediment loss from the heather catchment. The calibration of conditions within the "control" heather environment formed a contribution to a long term research programme, investigating both the hydrology of the catchment and catchment response to burning.

CATCHMENT SELECTION

In the selection of a catchment various theoretical and practical factors require consideration. Toebes and Ouryvaev (1970) have given some guidelines in the criteria for catchment selection.

The ecology of moorland management is such that the catchment needed to be small. Miller (1964) explains that the average territory of a pair of nesting grouse is approximately 4 ha.

Moorland management regimes attempt to provide a variety of heather types within this territory, varying from a dense cover for nesting purposes to open burnt ground for feeding. The selected catchment required a complete heather cover, to prevent confusion of cause and effect. Therefore, the ecology of moorland management required that the catchment should be relatively small (2 to 4 ha).

Access to the catchment was an important consideration. Catchment monitoring procedures required the transportation of bulky field instrumentation and samples, and therefore, access by road was desirable.

Field experiments often encounter the problem of human interference (e.g. Bridges and Harding, 1971). Consequently, the catchment needed to be removed from popular areas of the Moors. Furthermore, some facility was required to obscure field instrumentation from public view.

Access and installation of field equipment requires the permission and co-operation of landowners. Hence, the catchment area needed to be on the Estates of a co-operative landowner.

These criteria recommended the selection of Wintergill catchment, on the western flanks of Egton High Moor (G.R. NZ 763013) (Plate 1). The catchment is small and mostly covered with a monoculture of heather, some 25 years in age (B. Nellist, pers. comm.). Wintergill catchment is directly accessible by road, although Egton High Moor is not a major visitor area.

Discharge from the catchment is concentrated into a ditch and through a culvert to form a channel proper, which immediately enters Wintergill Plantation (G.R. NZ 761015). The installation of stream monitoring equipment within the plantation obscured the instrumentation from view, thus reducing the risk of external interference.

CATCHMENT DESCRIPTION

Wintergill catchment has undergone morphological changes, in particular the channeling of water into a drain introduces a certain amount of artificiality. However, the concentration of water enables the monitoring of a relatively large amount of water from a small area, covered by a monoculture of heather. Thus, water quality within the stream reflects the processes

operative within the catchment area. Runoff from the road was not considered a significant factor. Visual observation of runoff from the road during storm events demonstrated that most runoff is directed into the grassland on the western side of the road and not into the stream channel.

Toebes and Ouryvaev (1970) recommend that the topographic boundaries of experimental catchments be precisely defined. The generally flat nature of the upland surface of the North York Moors prevents a precise topographic delimitation of the catchment boundary. Furthermore, the topographic and phreatic boundaries of catchments are not necessarily synonymous (Ward, 1971). The identification of percolines, cusps and seepage lines provides a method of catchment delimitation (Bunting, 1964) but this approach necessitates a great deal of interference within the basin, also the hydrological boundary of catchments are dynamic through time. Consequently, Wintergill catchment was delimited by topographic survey, with distinct breaks in slope along the road providing markers for catchment delimitation. Levelling and plane table survey defined the catchment area as 4.7 ha (Fig.2).

A bench mark on the culvert revealed that the outlet of the catchment was at an altitude of 303.37 m O.D. The uppermost part of the catchment was at an altitude of 319.32 m O.D., therefore relative relief was some 15.95 m. Within the catchment slopes are quite gentle. A 202 m pantometer transect from the culvert to the catchment boundary revealed facets ranging between 0° and 22.5° , with a mean slope of 3.8° ($N = 146$).



Wintergill catchment is underlain by the Jurassic Estuarine Series (Fox - Strangways, 1892). No geological outcrops were observed within the catchment. The Estuarine Series is overlain by 30 cm to over 1.5 m of soil.

Examination of catchment soils allow their identification as Stagnohumic gley soils (Avery, 1973). The properties of Wintergill catchment soils accord with those identified as belonging to the Onecote Series (Bendelow and Carrol, 1976), a soil type widely distributed throughout the North York Moors associated with poorly-drained, gently-rolling moorland. Thus, the Wintergill soils are tentatively identified as belonging to the Onecote Series.

Soil characteristics were identified within a soil pit, dug in the centre of the pantometer transect. Plate 2 shows a typical soil exposure. The profile is described in Table 1.

The clayey texture of the Bg horizon made penetration to the C horizon difficult. A clay base was identified throughout Wintergill catchment during the insertion of neutron probe access tubes (C. Dunn, pers. comm.) The presence of a clay base suggests that the catchment is impermeable, indicative that loss of water by percolation from the catchment is low.

Kayll (1966) noted the unreliability of ring counting in assessing the age of heather stands. The general age was identified by the gamekeeper as 25 years old (B. Nellist, pers. comm.), although within the catchment all phases of the Calluna growth cycle (Watt, 1955) may be identified. Vegetation height along the pantometer transect varied between 0 cm, on lichen covered ground, to 46 cm in some of the dense mature stands. Mean vegetation height was

20.4 cm (N = 146).

On the extreme north of the catchment is an area of open, pioneer vegetation. The cover was burnt off in 1974 (B. Nellist, pers. comm.). The area covers some 0.51 ha, equivalent to 10.85% of catchment area.

Subordinate plant communities were found within the catchment which included shrubs such as crowberry (Empetrum nigrum), bilberry (Vaccinium myrtillus) and bell heather (Erica tetralix). Grasses include mat grass (Nardus stricta), soft rush (Juncus effusus) and bent grass (Agrostis tenuis) and a ground cover of Polytrichum commune and Cladonia lichens.

CATCHMENT INSTRUMENTATION

Instrumentation was installed to monitor various aspects of hydrological and geomorphological processes within the catchment. To evaluate sediment removal, instruments for the measurement of hydrological inputs and outputs were required. Thus rain gauges and stream recording equipment were installed.

Data on the magnitude of sediment movement within the catchment was collected using marked pebbles. Output sediment may generally be divided into several components. Sunley (1970) suggests that

"... the provision of an adequate definition of the different components of material moved by a river is one of the fundamental problems in geomorphological research."

Therefore, some consideration is necessary of the various components of sediment discharge and the optimum techniques for the monitoring and sampling of each component.

TABLE 1

Soil Characteristics
of Wintergill Catchment

a) Soil Profile Description

Horizons (cm)	
26 - 30 L	Heather litter
19 - 26 F	Partially decomposed litter
19 - 0 Oh.	Black (10YR/2.5/1). Loamy peat, some bleached sand grains, blocky, fine roots.
0 - 20 Eg.	Dark brown (10YR/3/3). Sandy, stony, blocky. Evidence of piping at top of horizon.
20 - 55 Bg.	Dark yellowish brown (10YR/6/3). Clay with ochreous streaks. Blocky, very fine.

b) Soil Property Analysis

Horizon	Oh	Eg	Bg
Depth cm.	19 - 0	0 - 20	20 - 55
% coarse fraction (by weight) (> 2 mm)	29.99	6.66	0
% fine fraction (< 2 mm)	70.01	93.34	100.00
% sand (0.063 - 2.00 mm)	78.81	33.82	22.69
% silt (0.002 - 0.063 mm)	7.84	51.23	32.14
% clay (< 0.002 mm)	13.35	14.95	45.17
pH	3.3	3.4	3.4
loss-on-ignition (%)	77.65	9.23	7.44
Moisture content (%)	64.79	25.53	73.39

The load of a stream is divided into solutes and solids, according to the chemical state of the material. Theoretically, total solids may be divided into wash load and bedload, (V.T. Chow, 1964), the former being in suspension and the latter in continual contact with the stream bed. Bedload material is transported from its stationary state by sliding, rolling or saltating. Wash load and bedload, however, are not mutually exclusive as saltating particles may be defined as wash load or bedload. Colby (1963) offers an arbitrary division based on the size of particles. Material with a diameter greater than 0.062 mm are considered to be bedload, or wash load if the diameter is less. Thus, suspended load consists of wash load and bed material temporarily in suspension, while bedload consists of material moving in contact with the stream bed.

The measurement of wash load and solute load required the sampling of stream water in various hydrological conditions. Thus, water samples were collected using an automatic water sampler while the collection of bedload required a collecting device to be inserted into the stream bed. In practise, bedload and wash load appeared to be distinct. Most of the bedload collected was composed of sand and gravel particles, by weight. Wash load consisted mainly of silts.

Having examined the processes which were to be monitored, and some of the techniques of monitoring, attention is now paid to catchment instrumentation.

i) Precipitation

Precipitation was measured using a Casella natural syphon autographic rain gauge. The gauge traced precipitation input

over time, allowing the extraction of various precipitation variables from the weekly charts. Rodda (1969) has demonstrated the tendency for standard rain gauges to underestimate precipitation compared with surface level gauges but as the latter were unavailable, standard gauge information was used. Values recorded by the autographic gauge were adjusted to the precipitation amount collected by an adjacent check gauge, using the procedure of Bruce and Clark (1966). Both gauges were sited centrally within the catchment (G.R. NZ 763013) and installed in accordance with Meteorological Office recommendations (Meteorological Office, 1956).

ii) Pebble Study

Intra-catchment sediment movement was monitored using tagged pebbles. Their use has been demonstrated in tracing sediment behaviour within an ephemeral stream in New Mexico (Leopold et al, 1966), in tracing sediment movement in Welsh catchments (Slaymaker, 1972), and on Canadian talus slopes (Gardner, 1979), while more sophisticated techniques have been employed by Butler (1977).

A total of 100 painted pebbles, of known weight, and measured axes, were located in the catchment in April 1978. 25 pebbles were placed in each of 4 ephemeral rills, the pebbles being placed at 10 cm intervals, with the heaviest furthest upslope. Retrieval took place in April 1979, when the distances moved were measured.

iii) Stream Discharge

Stream discharge was measured continuously with a 'v' notch weir and water level recorder. The thin-plate 'v' notch weir was sited

behind the instrument hut (Plate 2a) within which a weekly chart Munro water level recorder was installed (Plate 2b). A hole was cut into the floor of the hut which stood astride the stream, and the float inserted into a stilling well set into the stream bed. Variations in float level were marked on the recording chart.

A standard rating equation between stream discharge and water level was used (British Standards Institution, 1965; Walling, pers. comm.). The equation may be given as :-

$$2(1) \quad Q = 2.5 \left(\frac{\tan \theta}{2} \right) H^{2.5}$$

where Q = Discharge (cusecs)

θ = Included angle of 'v' notch (53°)

H = Stream height (feet)

The rating equation was converted to metric values, and simplified, to give the equation

$$2(2) \quad Q = 35.2946 (H \cdot 0.0328)^{2.5}$$

where Q = Discharge ($l \text{ sec}^{-1}$)

H = Stage (cms)

Calibration of the water level recorder remained reasonably accurate although some adjustment was necessary after storm events, due to sediment infill.

(iv) Water Sampling

Water samples were taken, at selected times, from the stream.

Gregory and Walling (1971) have discussed the value of automatic samplers. They facilitate the removal of samples when it is impractical for the researcher to be present, and offer a variety

of sampling programmes. Walling and Teed (1971) have compared the results of manual depth-integrated samples and those taken automatically, and found no significant difference.

A Rock and Taylor Automatic water sampler was installed within the hut, the inlet located 3 cm above the stream bed in the centre of the channel. The main sampling procedure was to connect the sampler to a mercury-filled switch in the stilling well. Rising discharge activated the float-switch at a pre-determined stage and sampling would take place at fixed intervals throughout the succeeding storm.

Water was pumped sequentially into 48 numbered plastic bottles, each with a capacity of 620 ml. The bottles were cleaned in distilled water before sampling began, and after each sample the pump reversed to remove remaining water from the tubes, thus preventing sample contamination. The sampler was powered by a 12 volt car battery. Automatically-pumped water samples were transported back to the laboratory for analysis. Stream stage, at the sampling time, was determined from the level recordings. Various aspects of water quality were examined. These included total particulate load, total suspended dissolved load, particulate organic load and dissolved organic load. The size-distribution of suspended solids was determined using Coulter Counter analysis. The techniques of analysis are described in Chapter 5.

v) Bedload sampling

The variety and sophistication of techniques of measuring bedload movement has been reviewed by Hubbell (1964). Researchers have employed traps, samplers, river structures and tracers while progress has also been made in the use of acoustic devices to

record the magnitude of bedload movement (Johnson and Muir, 1969; Richards and Milne, 1979).

In a review of the techniques available Painter (1972) concludes that bedload traps are the most satisfactory, despite their simplicity. Gregory and Walling (1971) have successfully used slot traps to collect bedload from small streams in Devon and a similar device was used in this study.

The trough measured the width of the stream, that is 65 cm wide, with a downstream length of 35 cm. A pit was dug into the stream bed and a tray placed into the pit, the uppermost lip being level with the stream bed. Two smaller traps, each with a depth of 20 cm were placed into the trough to facilitate ease of removal and the trough was emptied at monthly intervals.

Although simple in concept, various problems were encountered in the maintenance of the trough. Einstein (1950) recommends that the downstream width of the bedload collecting device should be 100 - 200 times the maximum bedload particle diameter to be totally efficient. Thus, the trough was efficient for fine gravel and sand-sized particles, which formed the bulk of bed material by weight, but of unknown efficiency for coarse gravel and the larger cobbles transported during flood events. Furthermore, during the large flood events associated with snow melt the trough often filled completely. Consequently, the efficiency of the trough was sometimes impaired.

Progress of Research

Hydrological monitoring of the catchment has been continuous since April 1978. Data reported in this Thesis are based upon data

collected between April 1, 1978 and March 31, 1979, thus covering an annual cycle. A number of problems were encountered in the maintenance of catchment instrumentation, in particular the lack of access during the severe Winter of 1978-79 caused gaps in data collection. Further problems were encountered due to occasional instrument malfunction and human and animal interference. Water sampling was extended for a further 6 months to enable the collection of water samples through a variety of hydrological conditions and the more accurate calibration of fluvial and sediment discharge.

The results of the catchment monitoring procedures are discussed later in the Thesis. Chapter 6 describes some of the salient characteristics of catchment hydrology. Chapter 7 analyses the characteristics of sediment discharge and discusses the quantitative assessment of sediment loss. In Chapter 11 the significance of the catchment results are discussed within the context of the research programme as a whole.

CHAPTER 3

EXPERIMENTAL DESIGN OF
THE EGTON HIGH MOOR SOIL PLOTS

INTRODUCTION

Field investigations within the Egton High Moor soil plots were directed towards a closer definition of some of the environmental processes operating within Wintergill catchment, by reducing the scale of investigation. The experiments were designed to investigate pedological processes within a controlled, vegetated environment and burnt moorland.

Three 400 m² plots were designated (G.R. NZ 766 017) being sufficiently small to allow the coherent integration of various experimental programmes, which included an investigation of surface-level changes within the two environmental states and observations of temporal changes in soil properties. Processes acting upon the soil surfaces were also examined, especially environmental temperature differences above vegetated and burnt ground.

An attempt was made to isolate the effects of fire intensity upon the environmental system. The two plots were burnt, one being much more intense than the other.

The location of the plots was determined by a number of factors. Sites adjacent to Wintergill permitted the extrapolation of catchment data to the soil plots (Fig.3). The selected areas were designated for burning by the Egton Estates Company, being integrated within their own burning programme. Furthermore, soil cover within the plots was rather shallow, allowing the insertion

of erosion pins down to bedrock and consequently increasing the reliability of the data obtained.

SOIL PLOT DESCRIPTION

Lithologically the plots were Jurassic (Lower Oolite) calcareous beds, of the Grey Limestone Series (Fox-Strangways, 1892) underlying a thin soil cover. At a depth of 6-0 cm an L and F layer were present, underlain by an Ah layer from 0-12 cm. The Ah layer lay above a Bs horizon, at a depth of 12-17 cm, overlying a Cu or R horizon. The soil characteristics, more fully discussed in Chapter 8, accord with those defining the Howard Series, a soil type associated with rigg-top sites (Bendelow and Carroll, 1976).

Surface slopes within each plot are generally low ($0-2^{\circ}$) and the Calluna cover was dated at 15 years old (B. Nellist, pers. comm.). Vegetation height was variable within the range 20 to 40 cm and the subordinate plant communities were mostly Polytrichum and Cladonia.

EXPERIMENTAL DESIGN

Each experimental plot measured 20 m by 20 m, this size being chosen to integrate different experimental programmes within a grid reference system. Two axes of the square were designated by either a letter or number. Thus, the north to south axis was denoted by letters, while the east to west axis was denoted by numbers. Each metre along both axes was denoted by a letter or number. Consequently, each plot had a grid network of 400 reference locations for use as sampling points (Fig.4). The plots were separated by 10 m of ground.

Within the grid reference network four sets of experiments were undertaken, a soil sampling programme, an erosion-pin investigation,

a microclimatic experiment and fire monitoring procedures. Each is described in greater detail below.

i) Soil Sampling Design

Soil sampling was undertaken to investigate temporal changes in soil characteristics, on both burnt and vegetated ground, over one annual cycle. The spatial heterogeneity of soil characteristics immediately complicates the separation of spatial variations in these properties from temporal trends. Variations in soil characteristics over short distances have been subject for discussion by Collins (1976) and Beckett and Webster (1971), while heterogeneity in soil characteristics within North Yorkshire uplands have been observed by Reid (1972) and Arnett (1974).

In an attempt to overcome the problem of spatial heterogeneity in soil properties the experimental areas were small, and soil sampling design based upon a hierarchical, systematic scheme. At each sampling period, at least 16 cores were removed from within each plot, and usually integrated into four larger samples. The pre-burn soil sampling was more intensive, with 25 samples integrated into 5 samples. A reported value for any particular plot, at a point in time, is the mean of the four or five values. Thus, each mean value is a grand mean on the top of a hierarchy of samples, and should be representative of that particular soil characteristic within the plot at that point in time. The analysis of four integrated samples should indicate the extent of spatial heterogeneity in soil properties and provide sufficient material for a variety of analytical tests.

Intensive periodic soil sampling was envisaged as the most commendable technique to determine spatial and temporal trends.

Thus, intensive soil sampling was conducted prior to the burns, on each plot, to yield data on control vegetated soil conditions. Further surveys were conducted six months and twelve months after the burns, investigating soil properties within both the control and burnt plots. More regular soil sampling surveys were considered, but evaluation of soil characteristics at a point in time might only be considered accurate if based upon a large number of samples removed from points throughout the plots. However, such regular sampling probably interferes with soil characteristics simply due to the bulk of soil removed. Consequently three intensive soil surveys were considered to balance the need for a large number of samples against interference due to their removal.

The aim of a sampling programme is to represent actual conditions within a population as accurately as possible. Hence, in terms of soil sampling within the plots, material must be taken from throughout the plots without bias to any particular area. A systematic soil programme was considered as the most suitable, enabling the collection of soil samples throughout the plots while preventing both interference with other investigations and the obvious impossibility of sampling at the same point twice.

To yield a wide cover of sampling points throughout the plots, a sample was always taken within each 25 m² quadrat of the plots (Fig.3). The initial sampling points were always in the extreme south-west of each quadrat, and subsequent samples taken 1 m diagonally from the previous sampling point. Some samples were taken immediately after the burns, consequently four sampling points were designated within each quadrat. The details of the

soil sampling programme are described in Appendix 1.

In an attempt to maintain comparability of results samples were taken to a standard depth. Evidence from the literature suggests that heather is a very shallow-rooted plant, Rennie (1957) reporting that 80% of Callunetum root systems are concentrated within the top 13 cm of the soil profile. However, Boggie et al (1958) suggest that heather root activity is concentrated in the uppermost 10 cm of soil, according to evidence on the movement of the isotope ^{32}P within labelled plants. Such a conclusion is supported by Chapman (1970) and Gimingham (1972). Hence, pedological processes associated with the presence or absence of the heather canopy might be expected to be concentrated within the topsoil. Thus, 10 cm-depth samples were taken from the plots. If this depth was not available at the relevant grid reference, the depth of actual soil was noted.

Samples may be removed by either augering or coring. Experience in Caydale, North Yorkshire, led Reid (1972) to recommend coring procedures which allow a more accurate determination of depth and do not disturb the particle-size distribution. A 15 cm long coring bit, with a sharp cutting edge and an access hole for the entry of samples 3.5 cm in diameter, was used. The bit was attached to a hammering device which allowed rapid insertion of the core into the regolith. This device has been described in detail by Reid (1972).

Soil cores were taken in the field and removed in-situ with a coring handle. The L layer was cut away exposing the organic and mineral substrate. Samples were stored in polythene bags and transported to the laboratory for analysis.

A variety of soil characteristics were investigated, including colour, moisture content, reaction, texture, organic content, cation exchange capacity and magnetic susceptibility. Analytical techniques and results are discussed in Chapters 5 and 8 respectively.

ii) Erosion Pin Survey

Surface level changes were monitored by the use of erosion pins. Many elaborate techniques have been described for measuring surface level changes (Campbell, 1970a) and Lam (1977), but generally these involve disturbance to conditions within the plots. A number of workers have recommended the use of erosion pins in small scale geomorphological studies including Leopold et al, 1966; Evans, 1967, 1971; Imeson, 1971; Bridges and Harding, 1971; Harvey, 1974 and Kirkby and Kirkby, 1974. Erosion pins facilitate measurements of surface level changes without great disturbance to natural conditions, and consequently a network of them was established within each plot.

At the beginning of the experiment pins were inserted into the plots at pre-determined reference points. The height of the pin above the surface, that is between the top of the pin and a surface washer, was noted. Re-surveying occurred one year later and any changes in pin height recorded. To overcome ambiguities which may arise due to frost-heave of the pins, the advice of Evans (1967) was adopted and the pins driven into bedrock. Thus, any changes in pin height over the year could be interpreted as surface level changes above.

A random distribution of pins often prevents their recovery due to screening by vegetation (Imeson, 1971). Consequently, the pins

were inserted systematically to allow rapid retrieval and to prevent erosion pin location interfering with soil sampling procedures. A pin was inserted into every 25 m² quadrat within each of the plots. Each pin location was 1 m diagonally south-west of the extreme north-east corner of each quadrat. Pin locations are shown in Fig.3 and their respective co-ordinates are reported in Appendix 1.

iii) Microclimatic Experiments

In Chapter 1 some of the processes acting upon the soil surface within a moorland environment were discussed. Available literature suggests that removal of vegetation by burning tends to expose the ground surface to a variety of processes, which were either inoperative or less effective on vegetated surfaces.

Barclay-Estrup (1971) describes various processes which act differently upon bare and vegetated soil surfaces, including air temperature, humidity, insolation, wind velocity and precipitation throughfall.

For a number of reasons, air temperature was considered to merit investigation. Differences in air temperature between burnt and vegetated ground is of considerable import to the faunal and floral ecology of Callunetum heathland while nivational processes affect soil stability (cf Chapter 1). Despite the importance of air temperature little data on relative temperature differences between burnt and vegetated moorland have been collected. Delaney (1953) reports temperature differences over a six-day period, while Barclay-Estrup (1971) measured weekly maximum and minimum temperatures over a two-year period on Elswick Heath, Aberdeenshire. However, these temperature recordings were taken within heather stands in various growth stages and were not intended to measure

differences between exposed and vegetated communities. Hence, as Barclay-Estrup suggests, there is a need for continuous long-term monitoring of microclimatic conditions.

Continuous temperature information requires automatic recorders, which function continuously over a prolonged period and require little maintenance. Such an instrument was used to measure air temperature differences between burnt moorland and heather moorland. A Negretti and Zambra recorder was installed on Egton High Moor subsequent to the first muirburn (Plate 3a). One temperature probe was positioned above the burnt ground while the other was inserted into an adjacent 37 cm-high heather stand. Both thermistors were placed within white plastic covers to reduce direct insolation and positioned 2 cm above the ground to minimise interference by micro-topographical differences.

The thermistors were calibrated before field emplacement and periodically checked against laboratory calibrated W.P.A. Multi-Probes, which demonstrated the accuracy of the recorder within $\pm 0.2^{\circ}\text{C}$. One small problem was that the maximum temperature recordable was only 30°C .

The information thus obtained refers only to temperatures recorded at two particular locations. Additional data on the vertical distribution of temperature, above the burnt and unburnt surfaces, were obtained from a set of pre-calibrated thermistors positioned periodically at heights of 67, 46, 32, 22 and 16 cm (Plate 3b).

iv) Fire Monitoring Procedures

The Egton High Moor soil plot experiments attempted to quantify pedological, micro-erosional and microclimatic processes operating

within burnt and vegetated moorland. The basic dichotomy between vegetated and non-vegetated moorland was extended to include the effects of differences in muirburn intensity. Several writers believe that intensity influences the environmental response (Whittaker, 1961; Whittaker and Gimingham, 1962; Kayll, 1966) and consequently the two plots were burnt at different intensities and the resulting effects examined.

Fire "intensity" has been correlated with fire temperature by Whittaker (1961) and Kenworthy (1964), although others have regarded it as a multi-dimensional phenomena affected by various aspects of the fires (Byram, 1959; Kayll, 1966). In this study aspects of fire intensity are examined within the two muirburns.

Fire temperatures have been measured using both physical or chemical instruments and electrical pyrometers. Physical/chemical pyrometers are materials whose properties change at a critical temperature. Organic pyrometers, which have known melting points, may be stored in metal containers and inserted into the soil profile prior to burning. This technique has been used in studies of temperature changes within soil profiles during forest fires (Beadle, 1940) and in heathland fire investigations by Whittaker and Gimingham (1962).

Several other types of physical pyrometers are available. Heat sensitive crayons or "thermocrons" were recommended by Miller et al (1955), while Silen (1965) suggests the use of heat sensitive pellets called "tempils". More recently, "thermocolours" have been employed, which change colour at critical temperatures and afford a relatively straightforward means of detecting temperature changes. Thermocolours may be painted onto mica strips which are

inserted into the soil profile (Whittaker, 1961; Lloyd, 1968). Their use is receiving further investigation at Aberdeen University (J. Hobbs, pers. comm.) and Southampton University (A. Hughes, pers. comm.).

A disadvantage of physical pyrometers is that they only yield data on discrete orders of temperature change, rather than actual temperatures. Thus, increasing usage has been made of electrical pyrometers (Kenworthy, 1963, 1964; Kayll, 1966) which allow continuous recordings of actual temperature during fires. Consequently, an electrical pyrometer was used to investigate fire temperatures during the muirburns.

Prior to each muirburn a chrome-alumel thermocouple was centrally located within the experimental plot (Reference K6), with the head projecting 2 cm above the surface. The leads were buried 4-5 cm below the surface and connected to the electrical pyrometer, located outside the burning area. During each muirburn, temperature measurements were taken every 10 seconds.

Some workers have suggested a multi-dimensional approach to assessing burning intensity and an index of fire intensity was proposed by Bryan (1959). The Index is the product of the heat of combustion, rate of fire spread and the amount of fuel consumed. Van Wagner (1964) defined the Index as

"... an expression of the fire rate of energy output per unit length of fire front"

and Kayll (1966) applied it to a quantitative evaluation of some Scottish muirburns. The equation is given as :-

3(1)

$$\begin{aligned} \text{Fire intensity} &= \text{Heat of combustion} \times \text{Rate of spread} \\ (\text{g cal sec}^{-1} \text{ cm}^{-1}) & \quad (\text{g cal g}^{-1}) \quad (\text{cm sec}^{-1}) \\ & \quad \times \text{Fuel consumed} \\ & \quad \quad (\text{g cm}^{-2}) \end{aligned}$$

Kayll (1966) calculates the heat of heather combustion as a constant $4,800 \text{ g cal g}^{-1}$. Assessment of the Index requires a measure for the rate of fire advance and the amount of fuel consumed during respective muirburns.

~~The rate of fire advance was measured by noting the time elapsed~~ for the fire to travel between markers spaced 1 m apart, a series of 20 pins being used. Fuel consumed was estimated by taking random vegetation samples before and after each burn. Vegetation sampling procedure followed that recommended by Robertson and Davies (1965) and Chapman et al (1975). A 0.5 m^2 grid was cast randomly over the plot before burning and all heather stands and litter within the grid removed and stored separately in plastic bags. The procedure was repeated after the fires. Moist weights and dry weights (after drying at 105°C for 24 hours) were determined, providing measures of the plant and litter moisture contents, the amount of fuel available and the amount of fuel actually consumed. Ancillary measurements were taken during the fires, including soil and air temperatures, wind velocity (measured every one minute during each fire, using a portable anemometer) and wind direction. Soil samples were also removed for determination of moisture content.

PROGRESS OF RESEARCH

The experimental design described above allowed an integrated examination of pedological, topographic and temperature changes within both a vegetated and burnt stands. Changes were also examined by comparing the two plots which had received different intensities of burning treatment.

The soil sampling programme was undertaken between March 1978 and April 1979. Pre-burn soil samples were removed from each plot between March 14 and 16, 1978. The northern-most plot was burnt on April 7 and the southern-most plot on April 24, the latter being the most intense. The third plot remained as a control, and during both muirburns the fire-monitoring procedures described above were carried out.

Successive soil sampling periods included removal of material immediately after each respective burn. Samples were also taken some six months (October 18, 1978) and one year later (April 24, 1979).

Erosion pins were inserted into the two burnt plots immediately following the muirburn and in the control plot on April 7, 1978. The pins were surveyed one year later (April 24, 1979) and all except three pins were re-surveyed.

Temperature charts were changed monthly with only 17 days of data being lost over an eighteen-month period. Two days were lost due to clock-mechanism failure and 15 days between mid-February and early March when severe wintry conditions rendered access impossible. Temperature profiles, above both the burnt and vegetated ground, were taken periodically with the W.P.A.

Environmental Multi-Probe.

The results from these experiments are discussed in Chapters 8 and 9, the former analysing results from the erosion pin survey and soil sampling programme and Chapter 9 being devoted to an examination of the temperature data. The significance of the findings, within the broad context of the current investigation, are given consideration in Chapter 11.

CHAPTER 4

THE SOIL MOVEMENT INVESTIGATION

In Chapter 1 the possibility of tracing soil particle movement on burnt and vegetated moorland soils was discussed. Such an investigation may contribute to our knowledge on the effectiveness of various potential soil transporting processes acting upon the surface within disturbed and undisturbed soils.

Technical problems in assaying soil particle movement necessitated a pilot study of soil tracing techniques, which is discussed below. The results and techniques acquired allowed the development of an experimental design for monitoring various processes, on a micro-scale, in both moorland types. Experimental design and the progress of the research programme are discussed later in the chapter.

Soil particle movement is a difficult process to measure directly. Sediment traps, fluorescent dyes and radio-active traces have all been employed (Morgan, 1978; Reynolds, 1966; Kazo and Gruber, 1962) but the potential of the last technique has not been fully considered. This technique relies on the principle that radio-active decay is a relatively simple phenomenon to detect and measure. Thus the movement of soil particles tagged with a known radio-active isotope may be directly monitored by examining the spatial redistribution of radio-activity

A number of isotopes have been recommended, including ^{46}Sc , ^{110}Ag , ^{32}P , ^{140}Ba , ^{59}Fe , ^{65}Zn , ^{134}Cs , ^{137}Cs , and ^{60}Co (Wooldridge, 1965) but to be useful they must satisfy several criteria. The isotope must label the soil particles irrespective of size, and be

retained despite leaching. Furthermore, the radionuclide must not remain active for too long nor pose an environmental hazard.

Current legislation, embodied in the Radioactive Substances Act (1960), stipulates that any radionuclide applied in field conditions must be surrounded by fencing until the time period of ten half-lives has expired. Consequently, the half-life of the selected isotope must be relatively short but also of sufficient duration to allow a period of field investigation.

^{59}Fe most readily satisfies the above criteria. Work by Nowland (1962), Wooldridge (1965), Kandil (1966) and Coutts et al (1968) has demonstrated the capacity of this isotope to label soil particles fairly uniformly, with a slight tendency for clay particles to absorb proportionally more ^{59}Fe . These workers also found that ^{59}Fe was retained, despite attempts at leaching. With a half-life of 45 days a field application must be fenced for 450 days, which does not restrict access for an excessive period but is sufficient to monitor soil movement. The International Commission on Radiological Protection (I.C.R.P.) has classified ^{59}Fe within Radionuclide Group III (I.C.R.P., 1977), a class of radionuclides with a low toxicity which are not considered an environmental hazard in the quantities used in the experiment.

The only published field application of soils labelled with ^{59}Fe to the natural environment was by Wooldridge (1965) in Oregon, U.S.A.. However, he did not employ the more sophisticated labelling techniques used by the Aberdeen University workers (Nowland, 1962; Kandil, 1966; Coutts et al, 1968), whose studies were confined to laboratory experiments and to exposures of soil trays to natural conditions. Since the Aberdeen work more sophisticated

techniques have been developed, such as liquid scintillation counting and autoradiographic microdensitometry, which may be used in assays of radio-active soil diffusion. This discussion describes the exposure of a soil sample to natural conditions and describes some of the techniques by which particle movement may be monitored.

THE PILOT STUDY

Location

A pilot study was designed to expose labelled soil in field conditions for a relatively short duration and assay any soil diffusion which had occurred. If the pilot study was successful the study would continue investigating soil mobility on both vegetated and non-vegetated sites. Sneaton High Moor (G.R. NZ 875 015) was the selected field area as public access is restricted, thereby minimising inconvenience caused by the obligatory fencing.

Sneaton High Moor lies to the eastern edge of the Central Watershed of the North York Moors (Fig.5), forming a ridge some 900 feet O.D. which slopes gently towards the valleys of Little Beck and the Murk Esk, to the east and west, respectively. The bedrock belongs to the Jurassic Estuarine Series and is overlain predominantly by an ironpan stagnopodzol (Avery, 1973). The surface organic layer is composed of wet peat some 20 cm in thickness, underlain by a moist highly-leached Eg horizon, with a discontinuous ironpan.

A vegetated monolith of soil measuring 1 m by 50 cm and 10 cm deep, situated on a 6° slope, was removed from the pilot site. Here the vegetation comprised predominantly heather (Calluna vulgaris) which belonged to the mature stage, according to the

four stage typology of Watt (1955). The heather cover was burnt in the laboratory with a gas burner and a sample of soil removed for labelling with ^{59}Fe . The sample was of the same dimensions as those employed by Kandil (1966) being cylindrically shaped, with a diameter of 10 cm and a depth of 1 cm. The sample, having a dry-weight of 19.3g, was extracted from the centre of the monolith. Subsequently the block was returned to the pilot site and the surrounding 25 metre square area fenced.

Labelling Techniques

The techniques of labelling follow the approach of Kandil (1966) and Coutts et al (1968). The Radiochemical Centre, Amersham, provided the ^{59}Fe in a 4 ml stock solution of ferric chloride ($^{59}\text{Fe Cl}_3$) in 0.1M HCl initially containing 400 μCi on June 12, 1978. This began the time datum from which to calculate decay. ^{59}Fe is an emitter of gamma rays and soft beta particles and decays to stable ^{59}Co .

Coutts et al (1968) demonstrated the increased absorption of ^{59}Fe by soil when the isotope is applied in vacuum with a chelating agent. Coutts et al compare the chelating agent ethylenediamine tetra-acetic acid (EDTA) with diethylenetriamine penta-acetic acid (DTPA) and found more ^{59}Fe absorption by soils using the latter, consequently DTPA was used in this study. Coutts et al found maximum retention of ^{59}Fe when the molar concentration of DTPA was 1 μM . However the molarity of the Fe Cl_3 was 1.4 μM compared with the 272 μM used in the present investigation. Thus, ^{59}Fe retention was tested with different molar concentrations of DTPA. The results suggest that increasing molar concentrations of DTPA, above 1 μM , tend to reduce retention (Table 2).

Labelling was undertaken in a vacuum desiccator, with an inlet valve to allow the radio-active solution to enter (Plate 4). The soil intended for labelling was placed in a beaker within the desiccator and allowed to evacuate for 1 hour. Initial tests used $4 \mu\text{Ci}$ of ^{59}Fe in a $^{59}\text{Fe Cl}_3$ solution varying from $40 \mu\text{l}$ to $62.8 \mu\text{l}$, depending on the stage of decay. The $^{59}\text{Fe Cl}_3$ was injected into a mixture of $1 \mu\text{M}$ DTPA, contained in $57 \mu\text{l}$ of DTPA solution, and 50 ml of de-ionised water. The water served to cover the soil during impregnation. Following evacuation the fluid was dripped slowly into the desiccator, thus covering the soil. The vacuum was maintained during the 24 hours of impregnation, the exposure recommended by the Aberdeen research.

Counting Procedure

Several methods exist by which radionuclide movement may be assayed, these include scintillation techniques and autoradiography. Scintillation is a direct method of counting radioactivity. In the investigation two scintillation devices, an Ekco Autoscaler and an Intertechnique SL 4000 Automatic Counter, were employed. For comparative purposes soil movement was also monitored using autoradiography. The techniques are described in greater detail below.

Initial counting tests employed an Ekco Autoscaler Type N 530 G, a scintillation counter with a well-type Na I crystal (Plate 5a). In most tests the counting procedure involved observing the number of seconds which elapsed for 1000 counts to be recorded. In all cases the background radiation (B.G.) was subtracted from the value. B.G. was taken as the mean of 3 separate counts, taken daily; the values varied between 3.1 to 3.4 counts per

second (C.P.S.). To standardise procedure all counts were based on 1 ml of sample, pipetted from the primary labelling solution, decanted solution or leachate.

Assays of labelled soil exposed in field conditions required a more sensitive scintillation system. Soil samples, after radioactive decay and diffusion over the ground surface, would possess low residual radio-activity. Thus, the most sensitive counting equipment was required and as sensitivity is at a maximum when the scintillant is in direct contact with the soil, the Intertechnique SL 4000 Liquid Scintillation System was recommended (Rapkin, 1968) (Plate 5b).

The sensitivity of the SL 4000 was optimised, and each soil sample was placed in a 22 ml plastic vial, to which 10 ml of toluene phosphor liquid scintillant was added. Each vial was counted for 10 minutes and the automatic printout gave the mean count rate per minute (C.P.M.). The values were adjusted to B.G. by subtracting the count rate given by a non-radio-active vial.

Autoradiography offers a relatively simple semi-quantitative method of assaying radionuclide movement (De Ploey, 1967; Evans and Syers, 1971; Anderson, 1978). Since ionising radiation darkens photographic plates, the exposure of highly sensitive film, in a light proof envelope, to radio-active soil produces a photographic impression of the distribution of radio-activity. Soil particle diffusion could be autoradiographed by exposures to the labelled soil in the field both at the beginning and end of the field experiment. The vertical displacement of radio-active soil could be measured by autoradiographing soil cores.

TABLE 2

IRON 59 RETENTION TESTS

⁵⁹ Fe applied in labelling fluid (μCi)	μM concentration of DTPA	Amount absorbed (μCi)	% retained
4	1	1.94	48.58
4	1	2.62	65.57
20	5	6.34	31.72
20	100	5.77	28.49
184	1	115.12	62.42

TABLE 3

SALT CONCENTRATION OF LEACHATES

Element	Chemical Constituent (Analar)	Concentration in leaching reagents (Mgl ⁻¹)
Cl	NaCl	1700
Ca	CaCl ₂ ·6H ₂ O	270
Mg	MgSO ₄ ·6H ₂ O	30
K	KCl	40
Na	NaCl	270
SO ₄	K ₂ SO ₄	700

The level of radiation largely determines the density with which the autoradiograph plate is darkened. Theoretically, a linear relationship exists between darkening and intensity, provided the exposure time does not exceed a 'threshold' after which no more darkening will occur. An examination of the variations in autoradiograph darkening might display soil particle movement if autoradiographs are taken at different points in time and the density of darkening analysed. Variations in plate darkening may be analysed using a micro-densitometer whereby a beam of light scans the autoradiograph and any filtering of light, due to plate darkening, is recorded by the movement of a pen. Micro-densitometry enables the analyses of both vertical and horizontal soil diffusion. A Joyce and Loebel Automatic Recording Microdensitometer Mark III C was used.

Leaching tests

Wooldridge (1965) and Coutts et al (1968) report strong retention of ^{59}Fe in labelled soils despite attempts at leaching in the laboratory. Resistance to leaching is crucial, as one must be certain that any diffusion of radio-activity is due to particle displacement and not to ^{59}Fe held in leaching reagents.

To evaluate ^{59}Fe retention a number of leaching tests were undertaken. In field conditions precipitation and soil moisture, containing a variety of salts, would percolate through the labelled soil. Hence, a number of leaching reagents found in natural conditions required testing. A review of the relevant literature indicated the types and concentration of salts in precipitation (Stevenson, 1968; Edwards, 1973(a); Cryer, 1976). The highest reported concentrations in mg l^{-1} were multiplied by a factor of

100 in the leachates used (Table 3).

Soil moisture may be expected to contain potential leachates, for instance the secretion of chelates by heather is regarded as a sesquioxide accentuating mobilization in heather dominated soils (Grubb et al, 1969; Grubb and Suter, 1971; Gimingham, 1975). Soil water samples were taken by percolating a mixture of the leaching reagents referred to on Table 2, in effect simulating chemically concentrated rain, through leaching tubes filled with soil from the test area. Precipitation samples were also used. The resulting leachates were used to test ^{59}Fe retention. The leaching reagents were slowly dripped through the radio-active soil, contained by a filter paper within a funnel, and the filtered residue collected for counting.

The leaching tests demonstrated the tenacity with which the ^{59}Fe is retained within the structure of the soil particle (Tables 4 and 5). The retention appears to be strong, irrespective of the ^{59}Fe activity absorbed in the soil. Hence, the leaching tests tend to confirm the assertion of previous workers that radionuclide displacement could be directly attributed to soil displacement rather than the movement of leachates.

FIELD EXPERIMENTS

The soil used in the pilot study was replaced into the monolith on August 7, 1978. The soil, weighing 19.2 g contained 94.7 μCi at the time of emplacement, equivalent to 4.93 $\mu\text{Ci g}^{-1}$ soil.

The radio-active soil was covered with plastic sheeting for 24 hours to allow the soil to moisten and become cohesive. During this period a Kodak Industrex Type C film (ASA 125), sealed in a

TABLE 4

RESULTS OF LEACHING TESTS
ON SOIL CONTAINING 1.94 μ Ci 59 Fe

Leachate	Volume (ml)	C.P.S. in resulting leachate	% of total activity removed in leachate
De-ionised water	N.D.	37	16 ¹ .0*
	250	2.64	1.19
	300	1.09	0.49
	350	0.43	0.09
	400 ^{2*}	-	-
Mg ^{3*}	50	-	-
Na	50	-	-
Ca	50	-	-
NaCl ₃	50	-	-
Soil moisture	100	5.11	2.33

TABLE 5

RESULTS OF LEACHING TESTS
ON SOIL CONTAINING 115.1 μ Ci 59 Fe

Leachate	Volume (ml)	C.P.S. in resulting leachate	% of total activity removed in leachate
De-ionised water	1128	3.0	0.024
Mg ³	50	2.0	0.016
Na	50	2.0	0.016
Ca	50	2.0	0.016
NaCl ₃	50	2.0	0.016
Soil moisture	100	2.41	0.019

*Notes

1. Figure includes radio-activity from washing excess 59 Fe off the soil, hence the value does not necessarily represent leaching.
2. Volume cumulative.
3. Solution mixed to form one leachate. It was intended that should any significant leaching occur the individual salt responsible for leaching would be identified. However no significant leaching occurred.

light proof envelope and moisture proof container, was exposed to the soil. The autoradiograph was placed over the plastic sheeting and held in position above the radio-active soil using weights. After the 24 hour period the sheeting and autoradiograph were removed, thus exposing the soil to erosive processes.

To measure the amount of rainfall available, which might displace soil particles, a rain gauge was installed within the compound. The gauge, sited in accordance with Meteorological Office recommendations (Meteorological Office, 1956), collected 84.1 mm of precipitation during the 44 days of field exposure.

After the exposure period the monolith was covered with plastic sheeting and an autoradiograph exposed for 9 days. The longer exposure was to allow an impression to be taken, despite the decay and diffusion which theoretically had occurred since the initial exposure. Subsequently, the sheeting was removed and soil cores taken from the block at pre-determined co-ordinates.

The sampling scheme was that used by Coutts et al. As one might expect greater variations in radio-activity levels near the source of the radio-activity, then the distance between sampling points should be less nearer the centre than further away. Thus, samples were taken at the centre of the monolith and at distances of 3, 9, 16, 24, 33, 43 and 54 cm. from the centre along the four diagonal axes joining the four corners of the monolith. The samples were taken with small tubes, with an internal diameter of 3 mm. To analyse vertical displacement a large core, 10 cm long and 3.5 cm in diameter, was extracted from the centre.

The soils were prepared for scintillation counting by forcing out

the soil from the core with a pushing rod. The top 1 cm of the soil was removed by scalpel. The mini-core was then placed in a plastic vial and allowed to dry for 24 hours at 80°C before adding the liquid scintillant. The counting procedure has been described above.

The results from the autoradiography, autoradiographic micro-densitometry and scintillation assay suggest a narrowly-defined areal and vertical displacement of the radio-active soil as comparison of the two autoradiographs in Plate 6(a, b) demonstrates. The areal diffusion can be directly observed on the micro-densitometer scans. Both plates were scanned through the centre and the micro-densitometer graph demonstrates the diffusion, of the order of 4 cm (Fig.6). The second exposure is denser due to the longer exposure time. The initial exposure shows a band of darkening some 10 cm wide, while the second exposure has a band of darkening approximately 14 cm wide. The second autoradiograph fades gently on the downslope portion of the plate, which probably represents some downslope soil displacement. This is confirmed by the results of the scintillation assay.

The results of the scintillation assay are shown on Fig.7. Cross sections were drawn plotting count rates against distance for each of the axes. From the axes discrete bands of count rates were extracted and interpolated onto a map (Fig.8) and for comparative purposes, the SYMAP Computer Package Program was used to interpolate data into a graphical form. The count rate categories follow the scheme used in the Aberdeen investigations.

The soil displacement is demonstrated in Fig.8 where one may observe a general downslope creep of soil. There is also a

general southward diffusion. Though explanations are tentative, one might hypothesize that the downslope movement is due to the greater efficiency of such soil transporting processes as rain-splash acting in a downslope direction. An interesting feature of the distribution is the symmetrical pattern of displacement along an east-west axis. There are two areas of activity, surrounded by soil with a lower activity. Both are approximately 15 cm from the centre. Again one might suggest rain-splash as a process dislodging particles and bouncing them a discrete distance.

The soil core taken from the centre was analysed for vertical diffusion, the sample being first split lengthwise. One half was divided into segments each 5 mm in length, which were placed in vials and analysed by scintillation counting, and the other half was placed in a box partially filled with sand to hold it firm. An autoradiograph was placed over the flat surface of the core and held in place by covering both the core and plate with sand. The plate was exposed for 25 days.

The results of the autoradiography and scintillation assay appear contradictory. While the autoradiograph shows a thin layer of radio-active soil, about 1 to 3 mm deep, on the top of the core, the scintillation assay suggests that the radio-active soil has diffused vertically into the soil (Fig.9). However, the diffusion recorded by the scintillation counter is non-random, the count rate decreases exponentially with increasing depth. The relationship can be given as:

4(1)

$$\text{Log } Y = 0.1209.X + 2.904$$

where

$$X = \text{depth (mm)}$$
$$Y = \text{count rate. (C.P.M.)}$$

The displaced soil does not show up on the autoradiograph, probably because the exposure time was insufficient to show such low-level activity. Nevertheless, the results suggest the possibility of using scintillation assays in examining vertical soil displacement.

CONCLUSION

The pilot study demonstrated some of the problems and potential of the radionuclide tracer technique in the examination of soil micro-erosion. As the technique offers the possibility of monitoring three-dimensional soil movement it was decided to continue work examining soil erodibility under different vegetation conditions on adjacent sites within Sneaton High Moor. Attention is now concentrated on the experimental design of these investigations.

EXPERIMENTAL DESIGN

Further studies on soil movement were concerned with spatial and temporal variations in soil diffusion on vegetated and burnt moorland. These studies used soils removed from field sites, which were subsequently labelled and returned to the sites. Thus assays of soil movement are fundamentally measures of "soil erodibility" (Morgan, 1979), rather than of soil movement within undisturbed sites. Hence, soil movement assays were measures of the net potential of processes to transport soils.

Spatial variations in soil movement were monitored on both heather-covered and burnt sites. To acquire information on temporal variations two sets of assays were carried out. One exposure was for six months, while the other was extended a further five months, thus demonstrating some aspects of seasonal variations in

soil mobility.

The techniques used were basically the same as those used in the pilot study, although a number of procedural modifications were necessary to enable further enquiry.

1) Laboratory Investigations

Field exposures of labelled soils were considerably longer than the pilot study exposure. To date, the longest reported field exposure of ^{59}Fe labelled soils was 80 days (Wooldridge, 1965). Considering the radio-active decay, and theoretical diffusion, which may occur, increased dosages of ^{59}Fe were necessary.

Statutory restrictions upon the experiment prevented more than 5 m Ci of ^{59}Fe being used within each set of experiments.

Considering such factors as decay, the magnitude of soil movement from the pilot study projected over time and the sensitivity of counting equipment, 2 m Ci of ^{59}Fe were considered sufficient for each individual assay. Since some 60% of applied ^{59}Fe appears to be absorbed, then 3 m Ci were applied to each set of soil.

Increases in dosage by a factor in excess of 20 over the pilot study dosage raised problems of radiological protection. Thus, laboratory work was conducted with a 5 cm thick lead shield between personnel and the source. Attendance at a course by the National Radiological Protection Board (N.R.P.B.) allowed the acquisition of safety procedures in the use of unsealed radioactive sources.

Considering the hazard potential only two further laboratory impregnations were carried out. In each case soil samples from both the burnt and vegetated sites were air-dried and mixed

together before labelling. After labelling the sample was divided in two, and stored in lead pots, before field emplacement.

Both labellings were conducted successfully. The main features of the impregnations are described in Table 6. Radio-activity figures are amounts based upon the time-datum.

Both sets of labelled soils absorbed more ^{59}Fe than expected, approximately 70% of the 6 m Ci of ^{59}Fe applied. Subsequently labelled soils were washed with 100 ml aliquots of de-ionised water. In both cases, 5 washes reduced the amount of free ^{59}Fe to less than 1% of the activity present in the soils.

For calibration purposes a soil sample was removed from each of the labelled soils. The calibration soil, plus the soil lost during washing procedures, reduced the soil available for emplacement on the Moors. In all 7.44 g and 9.1 g were lost in the first and second impregnations, respectively.

After washing the soils were divided into two portions, one portion for the heather plots and the other for the burnt plots. The labelled soils were subsequently returned to the field sites.

Assays of soil movement relied on scintillation counting. The decay of ^{59}Fe prevented the rapid monitoring of soil movement using autoradiography. Field experiments found that plates required exposures in excess of 1 month before the plates were sufficiently darkened. Nevertheless, autoradiography and autoradiographic micro-densitometry are useful techniques for short term monitoring of radio-active soil diffusion.

Soil cores for scintillation counting were removed from pre-determined co-ordinates using aluminium tubes, with an internal

TABLE 6

Characteristics of Laboratory Impregnation
of Soil Samples with ^{59}Fe

<u>CHARACTERISTICS OF ^{59}Fe</u>	FIRST LABELLING	SECOND LABELLING
Time datum for calibration	Nov. 27, 1978	June 11, 1979
Vol. of $^{59}\text{Fe Cl}_3$ (ml)	1	1.5
Activity of ^{59}Fe applied (m Ci)	6	6
<u>LABELLING CHARACTERISTICS</u>		
Date of labelling	Dec. 12, 1978	May 20, 1979
Wt. of soil sample (g)	59.01	59.89
Amount of ^{59}Fe absorbed (m Ci)	4.34	4.33
Amount of ^{59}Fe unabsorbed (m Ci)	1.66	1.67
% of ^{59}Fe retained	72.27	69.87
Activity of soil ($\mu\text{Ci/g}$)	78.9	72.3
<u>WASHING</u>		
No. of washes	5	5
Vol. of washing aliquot (ml)	500	500
Activity of last wash as a % of total ^{59}Fe in soil	0.65	0.87
<u>SOIL CHARACTERISTICS</u>		
Wt. of soil sample used for calibration (g)	0.0882	0.8859
Activity of calibration soil (μCi)	6.958	64.05
Wt. of soil placed in heather area (g)	25.8	23.73
Activity of soil placed in heather area (m Ci)	2.036	1.716
Wt. of soil placed in burnt area (g)	25.77	27.06
Activity of soil placed in burnt area (m Ci)	2.033	1.957

diameter of 1 cm. A soil mass of between 0.25 and 1.5 g represents the optimum for scintillation counting. Less soil would possess little radio-active material for counting, while more would greatly increase quenching or self-absorption. "Quenching" means that photons emitted from the soil are lost within the soil sample itself and not registered by the scintillation counter. With an internal diameter of 1 cm dry soil samples, with a depth of 1 cm, would possess weights within the range 0.25 to 1.5 g. Hence, soil cores with an internal diameter of 1 cm were used.

Soil sampling procedures were similar to those of the Aberdeen workers. The first assay was upon labelled soils exposed for six months. Extrapolation of the pilot study findings would suggest that soil diffusion would be of the order of 20-30 cms.

Consequently movement was assayed over a 1 m^2 area, on both the vegetated and burnt ground. Soil samples were taken from the centre and at distances of 3, 9, 16, 24, 33, 43 and 50 cm along the diagonal axes. Further cores were taken at 3, 9, 16, 24 and 33 cms along the perpendicular axes, giving 49 soil cores in total.

The longer exposure would theoretically result in greater soil diffusion. Results from the bedload data collected within Wintergill catchment (Chapter 7) provides evidence that sediment transportation is particularly high during spring flood events. Thus, the longer exposures were assayed over a 20 m^2 area. From each plot over 80 soil cores were removed. An intensive survey over the central metre square removed soil cores from the centre and at distances of 3, 9, 16, 24, 33 and 50 cm on the 4 perpendicular axes, thus yielding 27 soil samples. Over the remaining area a 50 by 50 cm grid was imposed. Soil cores were

removed at each grid intersection, giving a further 65 samples.

In the laboratory the top 1 cm from each core was removed and counted by the procedure described in the pilot study.

Scintillation results were adjusted to compensate for quenching.

Background radiation counted by the Scintillation Counter is related to the colour of the sample. Variability in B.G. was tested using various soil masses in scintillation vials. The correlation coefficient between C.P.M. and soil mass was $r = 0.845$ ($P < 0.001$, $N = 14$). The empirical equation may be given as :-

4(2)

$$\text{B.G. (C.P.M.)} = 40.7932 - (9.051 M)$$

where $M = \text{soil mass (g)}$

This empirical equation was used to adjust counts for B.G.

The second stage of data processing involved a correction factor for quenching. Samples of ^{59}Fe solution, containing 1.6 N Ci in 20 μl of solution, were pipetted into vials containing varying masses of soil. A positive correlation coefficient between percentage quenched and soil mass was found ($r = 0.714$, $P < 0.001$, $N = 12$). Scintillation counts were adjusted using the equation :-

4(3)

$$\% \text{ quenched} = 51.17 + 54.029 (g)$$

The corrected scintillation values were then interpolated into graphical form using the SYMAP Computer Package Program.

2) The Runoff Plot Study

The longer field exposures were carried out within runoff plots. Information on water quality and quantity released from the two plots was considered as useful ancillary data to the main soil diffusion experiments.

Various workers have commented upon the value of bounded runoff studies. Ward (1971) notes that

"... plot studies have been recommended both as an alternative to small watershed studies and as a complementary technique."

According to Morgan (1979)

"... bounded runoff plots gives probably the most reliable data on soil loss per unit area."

Runoff plots have been used in geomorphological investigations within a wide variety of environments. Their value has been assessed within temperate (Packer, 1951; Campbell, 1970(b); Dunne and Black, 1970), alpine (West, 1962; Soons and Rainer, 1968), semi-arid (Whitaker et al, 1961; Schreiber and Kincaid, 1967) and tropical environments (Kellman, 1969).

Two bounded runoff plots, each covering an area of 20 m², were installed on Sneaton High Moor (Plates 7a, 7b). The plots were bounded by lawn edging set into concrete. To prevent direct runoff from the concrete, the exposed concrete within the plots was covered over by local peaty material.

Boughton (1967) states that plot studies often interfere with natural conditions. However, bounded runoff plots were considered suitable for this study. Firstly, they allow the

collection of sediment and runoff from a precisely defined area. Secondly, it was considered desirable to contain the radio-active soil within a restricted area.

One plot was sited on vegetated ground while the other was sited on burnt ground. The upper part of the plots measured 5 m x 3 m, and narrowed to a point 5 m downslope of the uppermost edge (Fig.10). Runoff was funnelled through two 4 cm diameter tubes into a plastic runoff collector. The capacity of the collector was c. 18 litres. The collectors were emptied monthly.

Not all the runoff from the plots could be collected. High winter runoff meant that the containers often overflowed. Larger runoff collectors were considered. However, the remoteness of the site, which was an important factor in enabling work using an isotope, prevented the maintenance of larger collecting devices. Nevertheless, runoff samples proved useful for analysis.

For each runoff sample total runoff volume (l) was determined. Filtration allowed the measurement of sediment concentration (mg l^{-1}). Collected sediments and filtrates were tested for ^{59}Fe content, in both solid and solutional phases. Such investigations were considered as a field assessment of the resistance of labelled ^{59}Fe to leaching.

3) Field Investigations

The prolonged experiments were carried out adjacent to the pilot study site (Plate 8). To prepare the sites an area of some 900 m² was burnt by Forestry Commission Staff on November 3, 1978 (Plates 9a, 9b). The muirburn was monitored using the procedures described in Chapter 3. Subsequently, the area was

fenced, in accordance with statutory requirements.

Due to the severity of the 1978-79 winter necessary work on the runoff plots could not proceed until spring 1979. Both runoff plots were on a 6° slope, as defined by a pantometer survey. Two other 1 m^2 plots, both on a 6° slope, were designated. A rain gauge was installed centrally within the compound (Fig.10).

The soils for the six month assays were returned to the 1 m^2 areas on May 15, 1979 and covered by polythene sheeting for 48 hours, while an autoradiograph was exposed. The soils were sampled 188 days later, or 51.8% of the year later, on November 21, 1979.

Soils for the longer exposure were returned to the runoff plots on June 6, 1979, and autoradiographs taken. The plots were visited monthly. Precipitation collected by the rain gauge was measured and the runoff samples removed.

Soil movement was assayed on the burnt plot on May 12, 1980 and May 14, 1980 on the heather plot. Due to some errors in the shape of the heather plot not all the soil samples could be taken. A total of 94 soil samples were taken from the burnt runoff plot and 88 soil samples from the vegetated runoff plot. The samples were subsequently transported to the laboratory and counted using the techniques described above. The results of the experiments are discussed in Chapter 10.

The Institute of Hydrology established a Didcot model automatic weather station some 80 m south of the radiation compound (J. Roberts, pers. comm.). Soil moisture and wind velocity data recorded at the station are also discussed in Chapter 10.

CHAPTER 5

LABORATORY AND STATISTICAL TECHNIQUES

Soil and water samples collected within field areas were subjected to a number of analytical procedures. This chapter describes these laboratory techniques and the computational procedures adopted for collation and analysis.

Water Analysis

Analysis of water quality concentrated mainly upon the properties of automatically collected water samples from Wintergill catchment. Samples were contained in pre-washed plastic bottles and stored under refrigeration. Chemical and physical properties are often unstable under storage (Rainwater and Thatcher, 1960), thus the samples were analysed as soon as possible, usually with the six-day period recommended by Johnson (1971). Five tests were conducted always in the same order, these being :-

- 1) Coulter Counter analysis of the suspended solids.
- 2) Particulate suspended load.
- 3) Dissolved sediment load.
- 4) Particulate organic load.
- 5) Dissolved organic load.

These techniques are discussed in greater depth below :-

1) Coulter Counter Analysis

a) Introduction

The Coulter Counter is an instrument which may be used for the determination of the particle-size distribution of suspended solids. Initially, the device was used for the counting of blood

cells and algae (Maloney et al, 1962; El-Sayed and Lee, 1963), but geomorphologists have come to recognize its research potential (Eckhoff, 1966). Walker et al (1974) have demonstrated its usefulness in an investigation of suspended solids discharge within rivers in New South Wales.

Results from Coulter Counter analysis compare favourably with those gained by complimentary techniques. Swift et al (1972) have compared various microscopic, optical, sedimentation and electronic methods, concluding that

"... the Coulter Counter is in many respects the most versatile and satisfactory instrument available."

Some have reported a close correspondence between the results gained using pipette analysis and Coulter Counter analysis (McCave and Jarvis, 1973; Shideler, 1976).

b) Principles of Coulter Counter Analysis

The principles of Coulter Counter analysis have been described in detail by McCave and Jarvis (1973). Fundamentally, the disturbance introduced into an electrical field by suspended solids is calibrated and measured. A brine electrolyte is used within the electrical field, consisting of a 1% Na Cl solution, filtered through a 0.22 μm Millepore filter.

A known volume of electrolyte and sample is drawn through an aperture of known size. A constant electrical current flows between the electrodes on either side of the aperture. Suspended solid particles cause a change in resistance across the electrode, which can be related to particle volume.

c) Coulter Counter Calibration

The relationship between particle volume and voltage pulse may be determined using calibration techniques. Mono-sized particles, of known size, are introduced into the Coulter Counter in a brine solution and the maximum number of counts is related to the aperture size (Coulter Electronics Limited, Technical Manual, 1968). Using such procedures a size distribution for the mono-sized particles is computed and the median value is taken. Thus, a calibration of particle size and Coulter Counter setting is achieved. This relationship may be converted into volume, diameter or number of particles within a given size range, using standard equations.

d) Analytical Procedures

Calibration was undertaken using paper mulberry pollen having a median particle volume of $13.31 \mu\text{m}$, and a $200 \mu\text{m}$ aperture. Measured particles should be within the 2% to 40% size range of the aperture (Fleming, 1967). Thus, the Coulter Counter was calibrated to measure particles in the 6 to $71 \mu\text{m}$ range (Table 7) while periodic re-calibration demonstrated its stability.

Measurements were taken by extracting a 10 ml sub-sample from the agitated sample bottles, diluted with 100 ml of brine, and further agitated using an ultra-sonic probe.

The sample was then placed into the apparatus and a 0.5 ml sample (known as the monometer volume) extracted by the Coulter Counter, through the $200 \mu\text{m}$ aperture. Two counts were taken for each of the settings in Table 7. Subsequently, the background value, that is the number of measured particles within the brine, was subtracted from the mean number of counts.

TABLE 7

Settings on the Calibrated Coulter Counter

Settings		Magnification	Lower threshold setting ¹	Particle diameter counted (μ) ²
Amplification	Aperture current			
1/2	1/8	1/16	10	6
1	1/8	1/8	25	9
1	1/4	1/4	40	14
1	1	1	40	21
4	1	4	40	34
8	1	8	40	43
16	1	16	40	54
32	1	32	40	67
64	1	64	40	85

1. Upper threshold setting switched off, therefore counts were of all particles greater than the calibrated diameter.
2. The diameter counted was of particles equal or greater than the given particle diameter.

2) Particulate Suspended Load

Filtration of water and noting the change in weight due to the accumulation of sediments upon filter paper has been recommended as a technique for the determination of particulate suspended load (Eaton et al, 1969; Douglas, 1971; Burgess, 1976; Naiman, 1976; Arnett, 1978; Finlayson, 1978; Osborne et al, 1980).

While "Millepore" filters have been variously recommended (Eaton et al, 1969; Douglas, 1971), this study uses Whatman GF/C membrane filters, with a pore size of $0.4 \mu\text{m}$, (Loughran, 1977). Since being carbon free, these filters could be subsequently used for the determination of organic particulate load.

In the laboratory procedure a pre-weighed Whatman GF/C filter was placed within Millepore filtration equipment (Douglas, 1971). A known volume of streamwater was then filtered through the apparatus, under vacuum. The filter was then air-dried and kept in a desiccator, both procedures were employed for half an hour. Subsequently, the change in weight was calculated by re-weighing the filter and the increase in weight was converted to mg l^{-1} .

Some workers recommend the use of control filters, which allow the weight changes induced by some external factors to be introduced into the calculations (Guy, 1969; Burgess, 1976).

In an experiment control filters were used on 13 samples. Weight loss ranged from 0 mg l^{-1} to 0.8196 mg l^{-1} , with a mean of 0.340 mg l^{-1} . Considering the increased workload involved, such a slight increase in the accuracy of suspended solids load was not considered worthwhile.

3) Dissolved Particulate Load

The total dissolved solids content (T.D.S.) of streamwater may be

measured by the conductivity technique or by the evaporation method (Gregory and Walling, 1973). The latter technique was employed involving the evaporation of 250 ml aliquots of stream water in pre-weighed nickel dishes over a stream bath. After evaporation the base of the dishes were cleaned, the dishes re-weighed, and the increment in weight was converted into mg l^{-1} .

The evaporation technique systematically underestimates solute concentration. Upon drying calcium, magnesium and chloride salts loose weight, water of crystallisation is lost from sulphate and magnesium compounds and bicarbonates are converted to carbonates (Rainwater and Thatcher, 1960). Despite the underestimation of solute content, results are reproduceable to $\pm 0.5 \text{ mg l}^{-1}$ (Burgess, 1976).

4) Organic Load

The literature describes three major techniques for the determination of fluviially transported organic matter. Organic content may be measured by the technique of wet oxidation, whereby organic matter is oxidised by potassium dichromate, in the presence of sulphuric acid (Strickland and Parsons, 1968). The ultra-violet absorption method involves the examination of the ultra-violet absorption of a water sample, when exposed to ultra-violet radiation, on a calibrated spectrophotometer (Armstrong et al, 1966; Banoub, 1973). An alternative procedure is infra-red gas analysis (Menzel and Vaccaro, 1964; Baker et al, 1974; Naiman, 1976; Mulholland and Kuenzler, 1978; Bilby and Likens, 1979). Irradiation with ultra-violet light oxidises the organic carbon within a water sample to form carbon dioxide (CO_2). An

infra-red gas analyser automatically registers the liberation of CO_2 . Thus organic carbon content is estimated using a calibration between organic carbon and CO_2 .

Wet oxidation appears the most applicable technique for the determination of organic matter and may be employed for the determination of both particulate and solutional phases. Ultra-violet absorption has only been used for the determination of dissolved organic matter (Armstrong et al, 1966; Banoub, 1973). Infra-red gas analysis has been mainly restricted to the analysis of dissolved organic matter (Menzel and Vaccaro, 1966). Baker et al, (1974) attempted to use the technique upon the particulate phase, but results were only reproduceable to $\pm 5\%$.

Evidence suggests that the three techniques are comparable.

Williams (1969) reports the reproducibility of results using wet oxidation and ultra-violet absorption techniques. Ultra-violet absorption results were slightly higher, with a mean of 0.07 mg l^{-1} more organic matter. Williams concludes that

"... the Menzel and Vaccaro wet oxidation method is not missing an appreciable amount of dissolved organic carbon."

Menzel and Vaccaro (1964) report comparability of results using the wet oxidation and infra-red gas analysis techniques.

Geomorphologists have tended not to use the ultra-violet absorption or infra-red gas analysis techniques, usually employing the wet oxidation technique, which has been found applicable within a wide variety of fluvial environments (Fisher, 1970; Hobbie and Likens, 1973; Brunson, 1976; Naiman, 1976; Arnett, 1978; Finlayson, 1978; Naiman and Sibert, 1978;

Bilby and Likens, 1979). Thus the flexibility, reproducibility and available literature recommend the use of the wet oxidation technique within this study.

The wet oxidation methodology are based on those of Maciolek (1962) and Menzel and Vaccaro (1964). Organic matter within samples is oxidised with an excess of potassium dichromate in the presence of concentrated sulphuric acid. Heat accelerates the reaction and the excess dichromate is determined titrimetrically in the presence of orthophosphoric acid, using ferrous sulphate.

Quantitative oxidation produces a value for the weight of oxygen consumed (O.C.) in the oxidation process. This value may be converted to the weight of the organic matter if the oxygen equivalent (O.E.) is known. O.E. is the weight of oxygen (mg) required for complete oxidation of a unit weight of organic matter. Maciolek (1962) has shown O.E. to vary between 1.4 and 1.5 for different organic substances, a general figure of 1.43 being recommended. Multiplying the O.C. value by the O.E. reciprocal produces an estimate of the organic matter in the sample.

Particulate organic load was determined by oxidising the sediment retained on a Whatman GF/C filter. Dissolved organic load was determined by oxidising a 250 ml aliquot of filtered streamwater. Oxidation was accelerated by heat and the organic content noted in mg l^{-1} . Laboratory procedure is described in greater detail in Appendix II.

SOIL ANALYSIS

Field observations on the characteristics of soils were in accordance with those recommended by the Soil Survey of England and Wales (Soil Survey, 1960). Soil samples were collected from various field sites for laboratory analysis. A variety of tests were used. These include :-

- 1) Colour
- 2) Moisture content
- 3) Reaction
- 4) Organic content
- 5) Textural analysis
- 6) Cation exchange capacity
- 7) Magnetic susceptibility
- 8) Specific gravity

Whenever possible the techniques used were those recommended by the Soil Survey (Avery and Bascomb, 1974) or by the British Standards Institution (British Standards Institution, 1967). The procedures are described in detail below.

1) Soil Colour

Soil colour was defined with reference to Munsell Charts, based on the attributes of Hue, Value and Chroma (Pendleton and Nickerson, 1951). Hue indicates the relationship of the colour to the spectral colours of yellow, red or blue. Value represents the lightness or darkness of the soil, while chroma indicates the intensity of pigment. Colour was defined by comparing a moist soil fragment with Munsell Colour Charts.

2) Soil Moisture Content

The techniques available for the determination of soil moisture content have been reviewed by Curtis and Trudgill (1974). Methods include the use of tensiometers, electrical resistance methods, thermo-gravimetric techniques and neutron scattering techniques. Reid (1971) accords with the recommendation of Rider (1958) that the thermo-gravimetric technique is

"... the most simple method available and it has the attraction that the answer, once it has been obtained, is completely unambiguous."

Consequently, ~~soil moisture content measurements were taken using~~
the thermo-gravimetric technique.

A random sample, weighing 50-60 g, was taken from the soil sample requiring moisture content determination. The sub-sample was weighed, air-dried at 105°C for 24 hours, and re-weighed. Percentage moisture content, by weight, was measured using the formula :-

5(1)

$$\frac{\text{wet weight} - \text{dry weight}}{\text{wet weight}} \times 100$$

Subsequent soil analyses were conducted upon the air-dried soil, after drying at 105°C for 24 hours. Most tests were carried out on the fine-earth fraction (i.e. particles with a diameter less than 2 mm). The techniques of separation will be discussed in the section on soil textural analysis.

3) Soil Reaction

Soil reaction, or soil pH, was measured using a 1:2.5 suspension

of soil in water. A 10 g dry fine-earth sample was mixed with 25 ml of distilled water. The mixture was stirred, allowed to stand for 10 minutes and stirred again. A pre-calibrated glass electrode assembly was inserted into the mixture and soil pH measured. The above technique is that recommended by Avery and Bascomb (1974).

4) Soil Organic Content

Soil organic matter is determined by oxidation of the organic matter, whether by chemical oxidation or combustion. The latter technique has been examined by Ball (1964) who reports that weight loss in a sample which undergoes combustion is not always attributable to the loss of organic matter. The rapid procedure, of igniting a soil sample at 850°C for half an hour in a muffle furnace, allows weight loss due to loss of CO₂ from carbonates in calcareous soils, loss of elemental C and loss of structural water from clay minerals. Ball found such losses to be reduced using the longer loss-on-ignition technique, that is 375°C for 16 hours.

Most workers recommend the use of chemical oxidation to determine soil organic content (Maciolek, 1962; Bascomb and Avery, 1974). In principle, the procedure is that employed for the determination of streamwater organic matter. A soil sample is oxidised by potassium dichromate in the presence of concentrated sulphuric acid. Excess potassium dichromate is titrated against standardised ferrous sulphate. Standard equations allowed the percentage organic content, by weight, to be calculated. The procedure employed was that prescribed by the British Standards Institution (1967), modified for the analysis of the fine-earth fraction.

Details of laboratory procedure are described in Appendix III.

Despite some of the inherent inaccuracies of the loss-on-ignition method, the technique does allow a rapid assessment of soil organic content. The reproducibility of results was tested using replicate sub-samples from 12 soil samples from the Egton Moor Soil Plots. Organic content of one set was tested by loss-on-ignition (850°C for half an hour) while the other set underwent wet oxidation with potassium dichromate.

Correlation analysis of the results shows a close correspondence of the results ($r = 0.769$, $P < 0.01$, $N = 12$) (Fig.11). However, loss-on-ignition tended to yield higher organic contents. Mean soil organic content using loss-on-ignition was 16.67%, compared with 13.19% using wet oxidation. Thus, loss-on-ignition does tend to over-estimate organic content, compared with the generally accepted wet oxidation method. However, the close correspondence of results does suggest that loss-on-ignition may be used as a reasonable indicator of soil organic content.

5) Soil Textural Analysis

Initial analysis of soil texture involved the separation of the air-dried sample into coarse fraction (> 2 mm) and fine-earth fractions (< 2 mm), after grinding in a mortar with a pestle. Separation was carried out using a sieve.

Analysis of the fine-earth fraction involved the removal of organic matter using hydrogen peroxide. Material sizes in the sand-size range were found using standard methods of sieve analysis (Guy, 1969).

The silt-clay fractions were analysed by pipette analysis.

Pipette analysis assumes the operation of Stoke's Law, that particles in a liquid medium will settle at a velocity determined by particle size. However, various inadequacies are inherent in the procedure. Most workers assume a constant specific gravity for sediments of 2.65, but specific gravity can vary from 2.50 for quartz to 4.0 for limonite (Townsend, 1972). Furthermore, the procedure assumes particles to be spherical, when in fact silts and clays may be in rod-like or plate-like forms. Nevertheless, most workers recommend the procedure as reasonably reliable (Akroyd, 1964).

Laboratory procedure involved the wet sieving of the inorganic fine-earth fraction followed by drying and dry sieving. Material coarser than 63 μm are separated into size classes by sieving. Material finer than 63 μm are separated using sedimentation, whereby samples are pipetted from the sedimentation tube at pre-determined time intervals. These time intervals correspond to the settling times of given particle sizes. The procedure is more fully described in Appendix IV.

Results from pipette analysis were converted to percentage weight less than a given diameter. The data enabled the construction of cumulative grain-size curves and the calculation of the weights of the various textural groups, which were classified using the International size-limits (Avery, 1973).

6) Soil Cation Exchange Capacity

The cation exchange capacity of air-dried fine-earth fractions was measured using the procedure recommended by Avery and Bascomb (1974) based on that of Bascomb (1964). Fundamentally, the test involved the saturation of a soil sample with a chosen cation.

Excess saturating solution was then removed and the amount of cation exchange determined titrimetrically.

Buffered Barium Chloride solution was used as the saturation agent. Barium cation absorption was tested titrimetrically with standardised magnesium sulphate solution and E.D.T.A. solution, in the presence of ammonia and an indicator. Laboratory procedure is described in Appendix V.

7) Soil Magnetic Susceptibility

The magnetic susceptibility of sediments has been recommended as a parameter in the investigation of the magnetic properties of sediments. Advantages of magnetic susceptibility measurements are that they are rapid and non-destructive (Bloemendal et al, 1979). Magnetic susceptibility (χ) may be defined as the

"... ratio of magnetisation produced in a substance to the intensity of the magnetic field to which it is subject."

(Bloemendal et al, 1979).

The magnetic susceptibility of selected soil samples were measured on a coil magnetic susceptibility meter at the University of Liverpool. For comparative analysis readings were converted into mass per unit volume.

8) Soil Specific Gravity

Specific gravity measurements were occasionally made upon dry fine-earth fraction samples. Measurements were made by calculating soil weight per unit volume of soil, using specific gravity bottles. The technique is described in detail in Appendix VI.

Statistical and Computational Procedures

Automatic field instrumentation and laboratory analysis allowed the acquisition of data. Data were processed and analysed using a number of computational procedures.

Preliminary statistical analysis was afforded with the use of a Tectronix mini-computer. Package programs and purpose written programs, in Basic language, were used.

Processing of continuous stream stage recordings was undertaken with a D. Mac Digitiser (Rogers and Dawson, 1979). Hourly stage measurements were rendered into strings of co-ordinates and the punched tape inserted into the file store of the University ICL 1900 series computer.

Longer statistical calculations were carried out on the University ICL 1900 series computer. Data processing and analysis were facilitated with the use of Statistical Package for the Social Sciences (S.P.S.S.) package programs and the SYMAP Package Program (Cerny, 1972).

OVERLEAF.

PLATE 1 (a) Wintergill catchment.

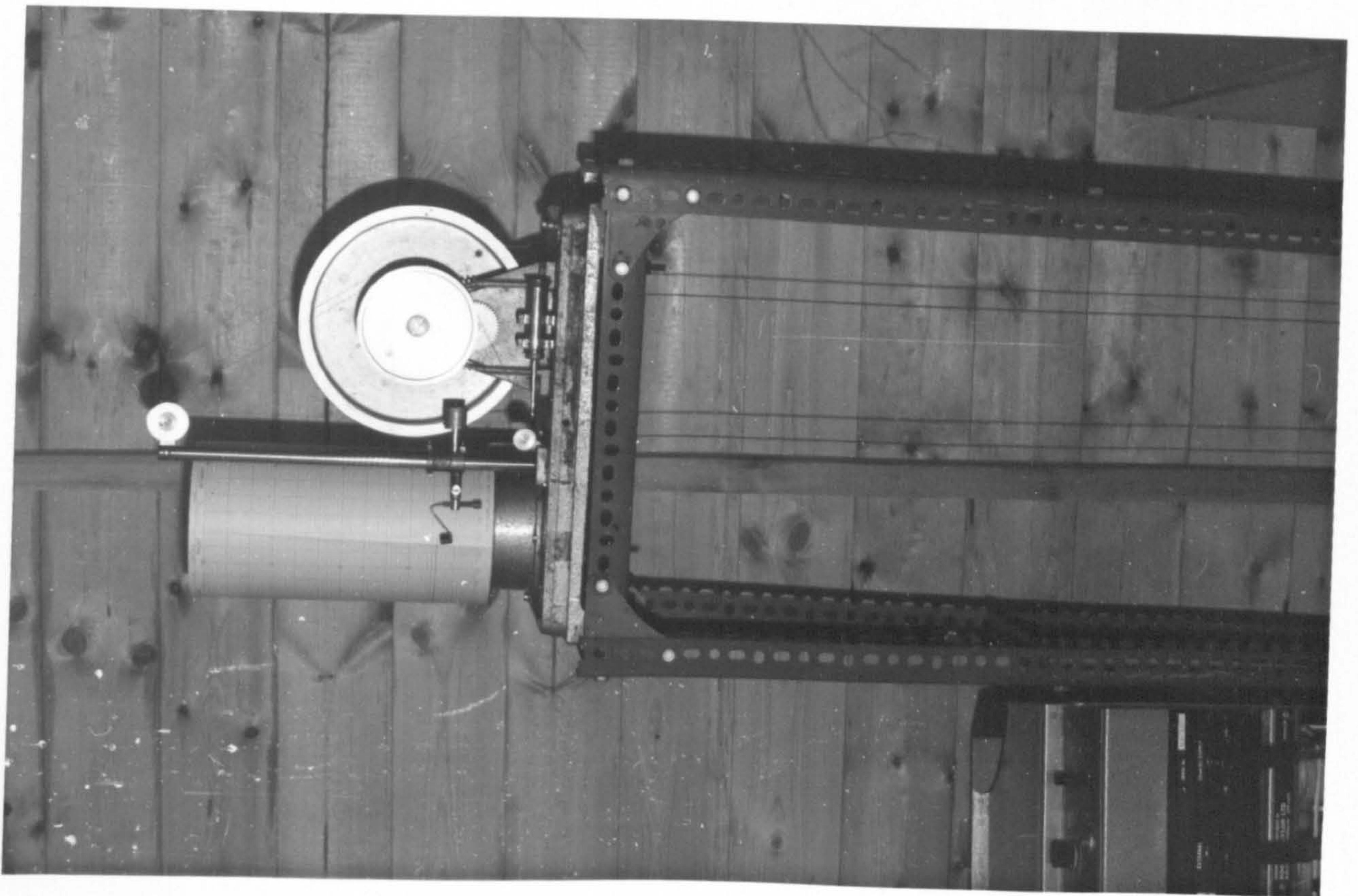
PLATE 1 (b) Wintergill catchment soil profile.



OVERLEAF.

PLATE 2 (a) " V " notch weir.

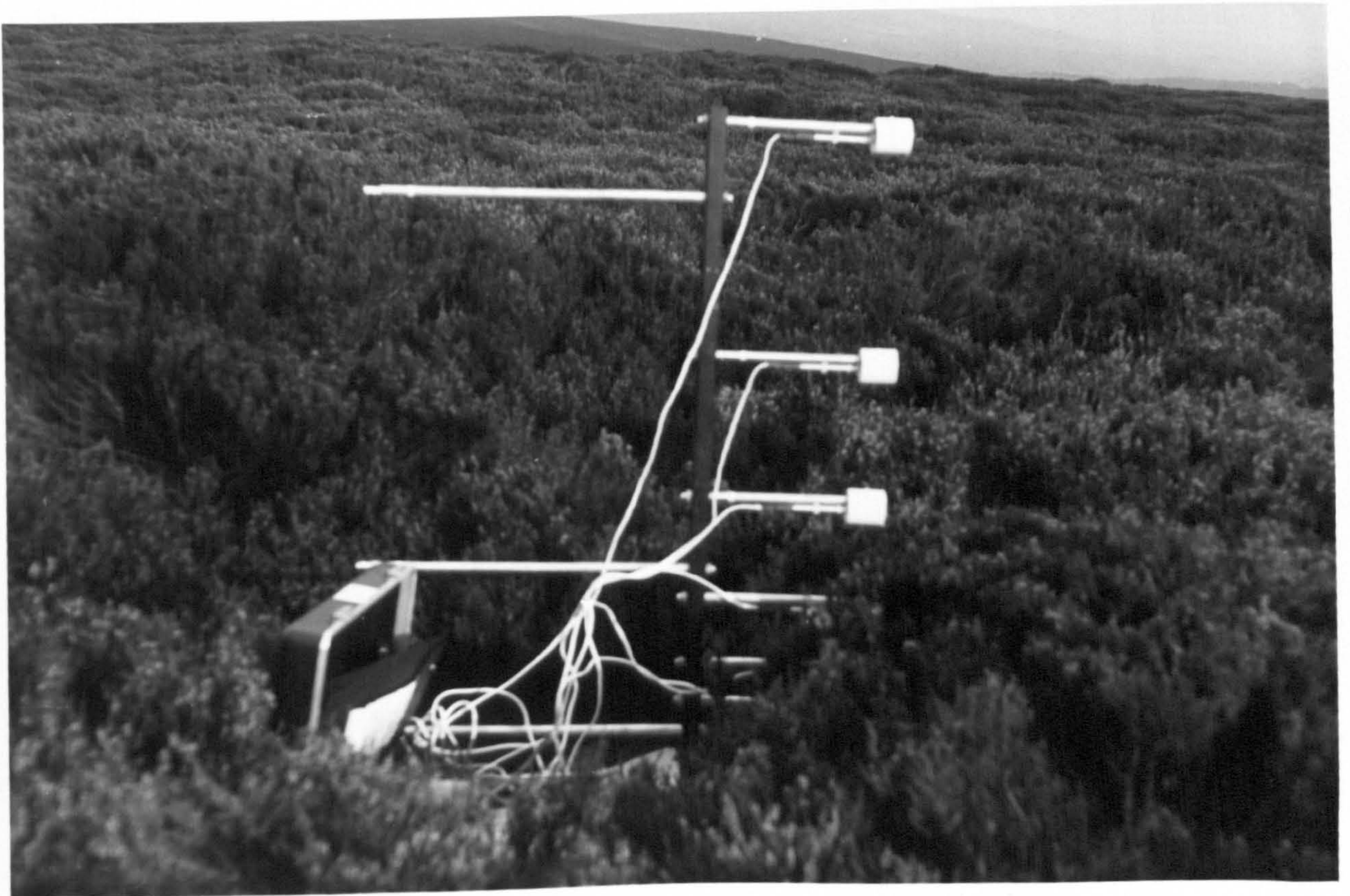
PLATE 2 (b) Shed instrumentation.



OVERLEAF.

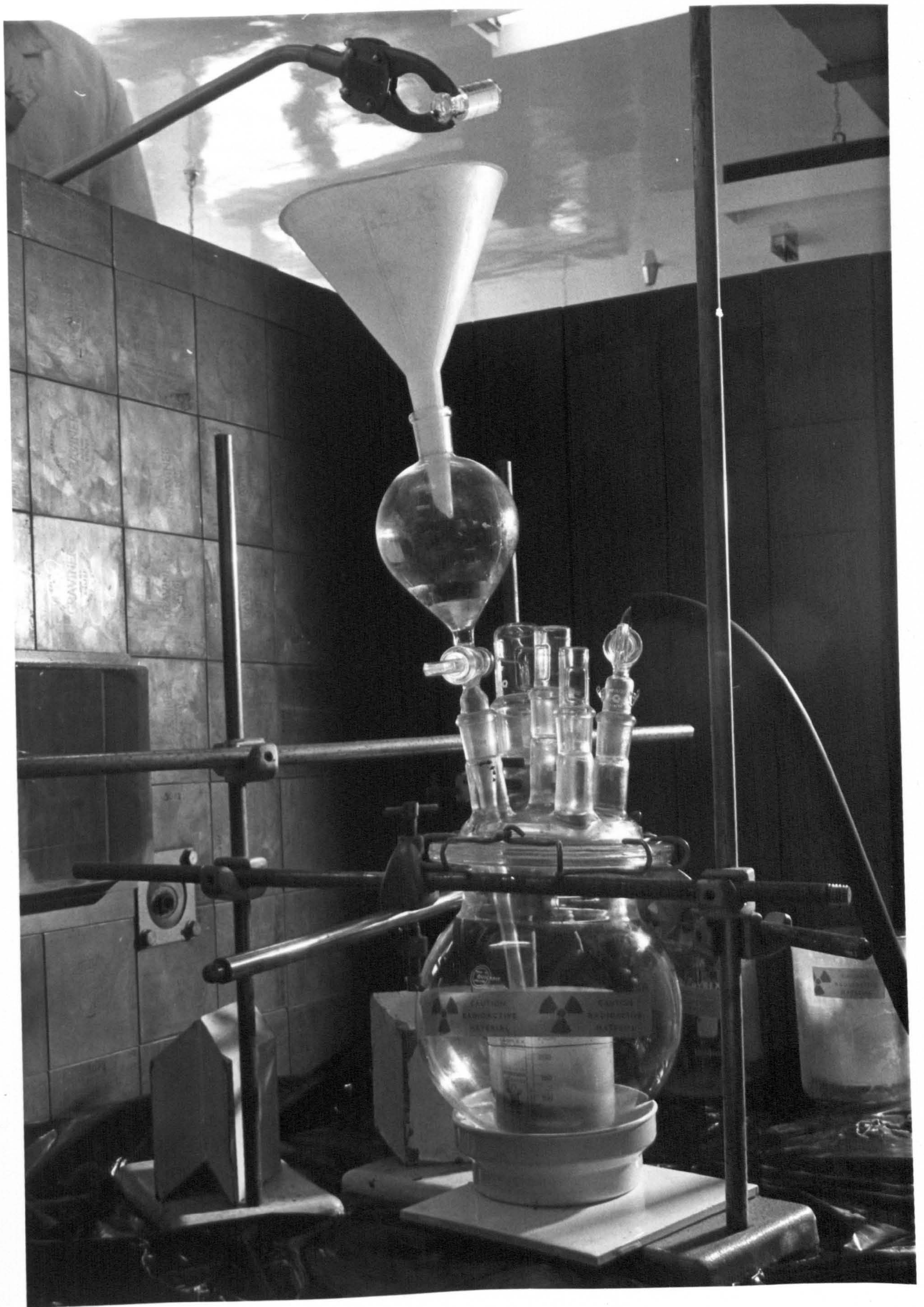
PLATE 3 (a) Automatic temperature recorder.

PLATE 3 (b) W.P.A. Environmental Multiprobe.



OVERLEAF.

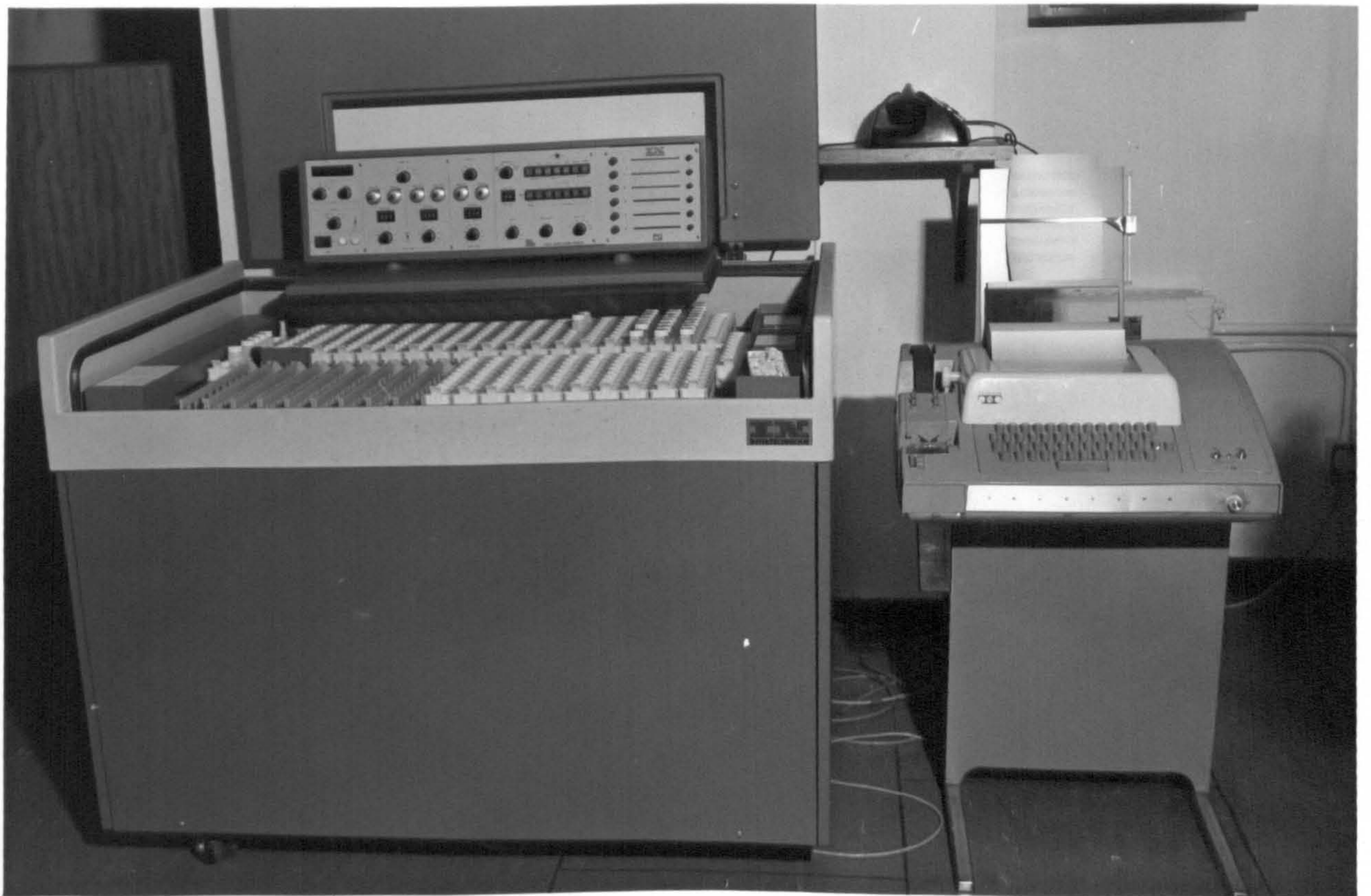
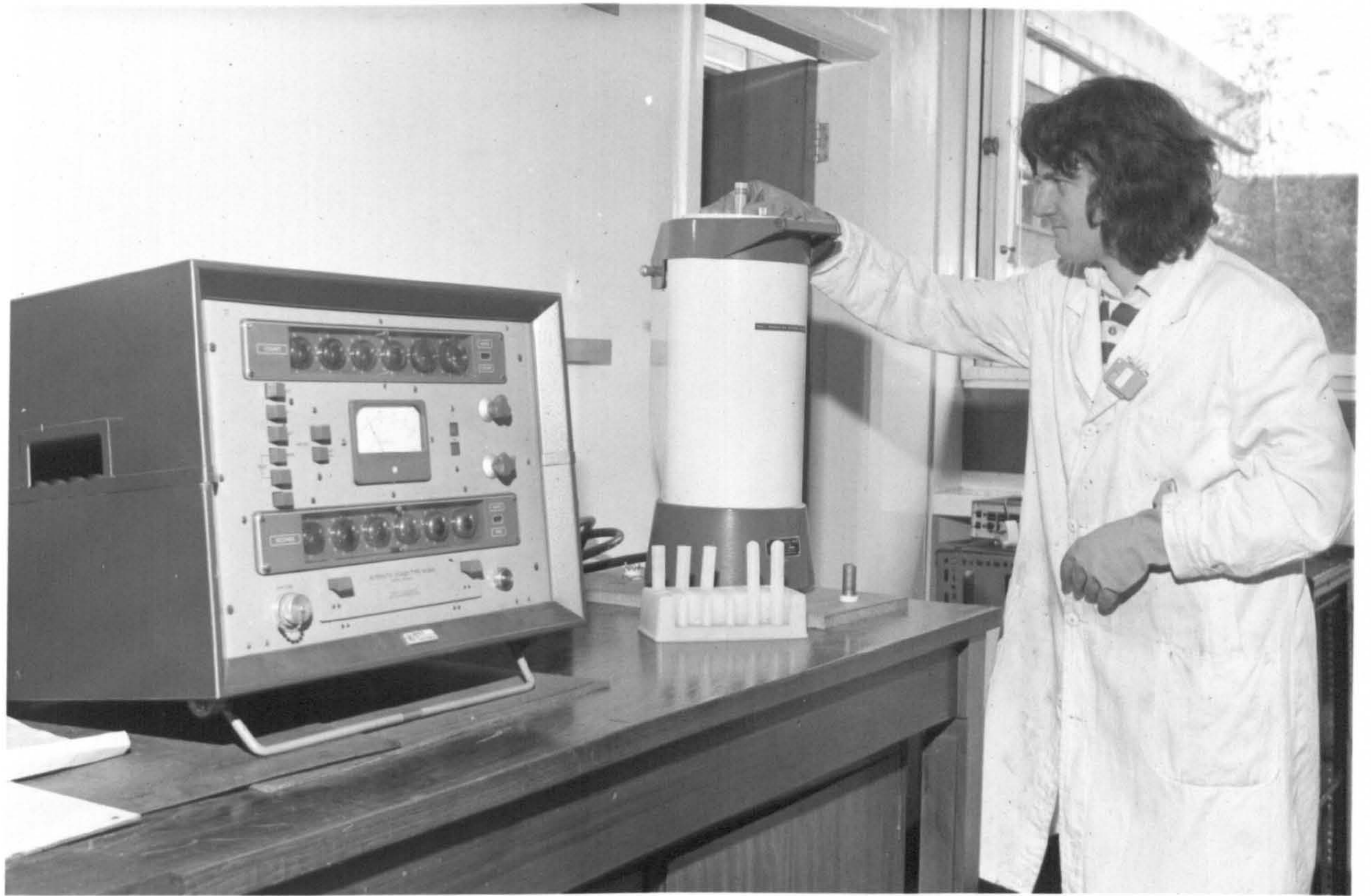
PLATE 4 Labelling vacuum desiccator.



OVERLEAF.

PLATE 5 (a) Ekco Autoscaler Type 530 G Scintillation Counter.

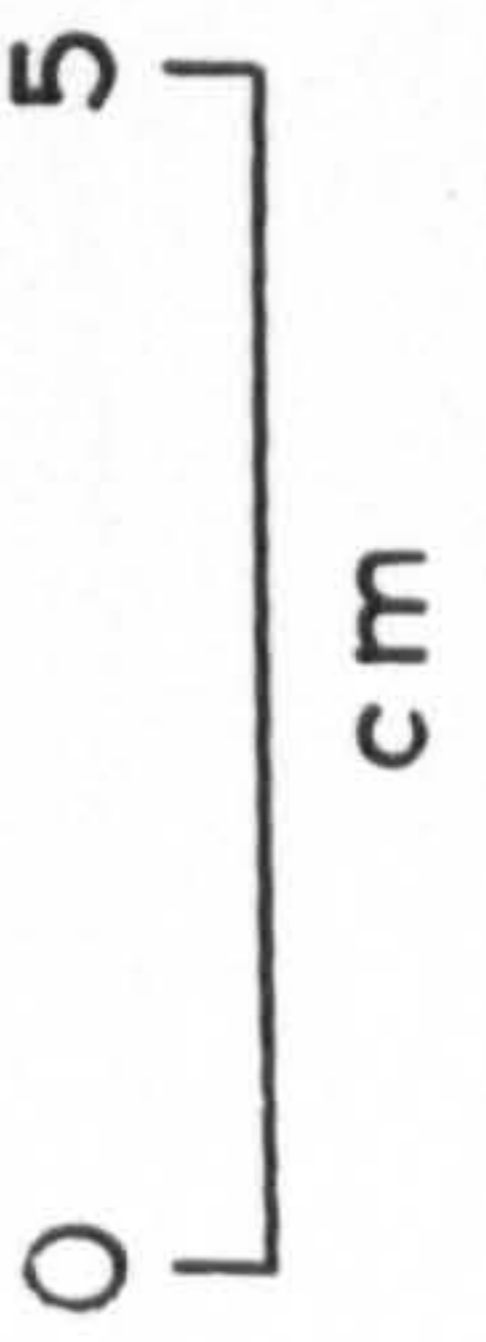
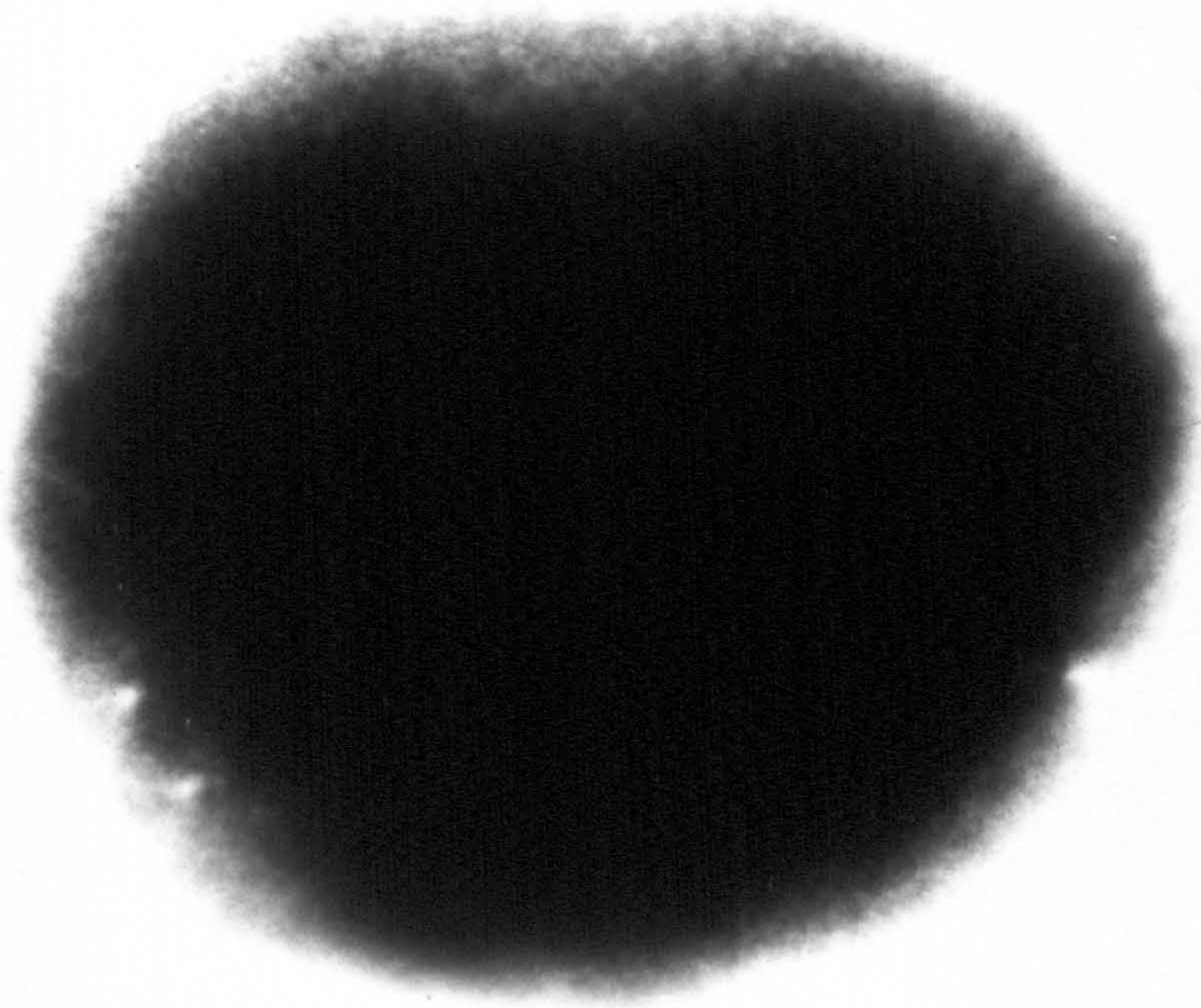
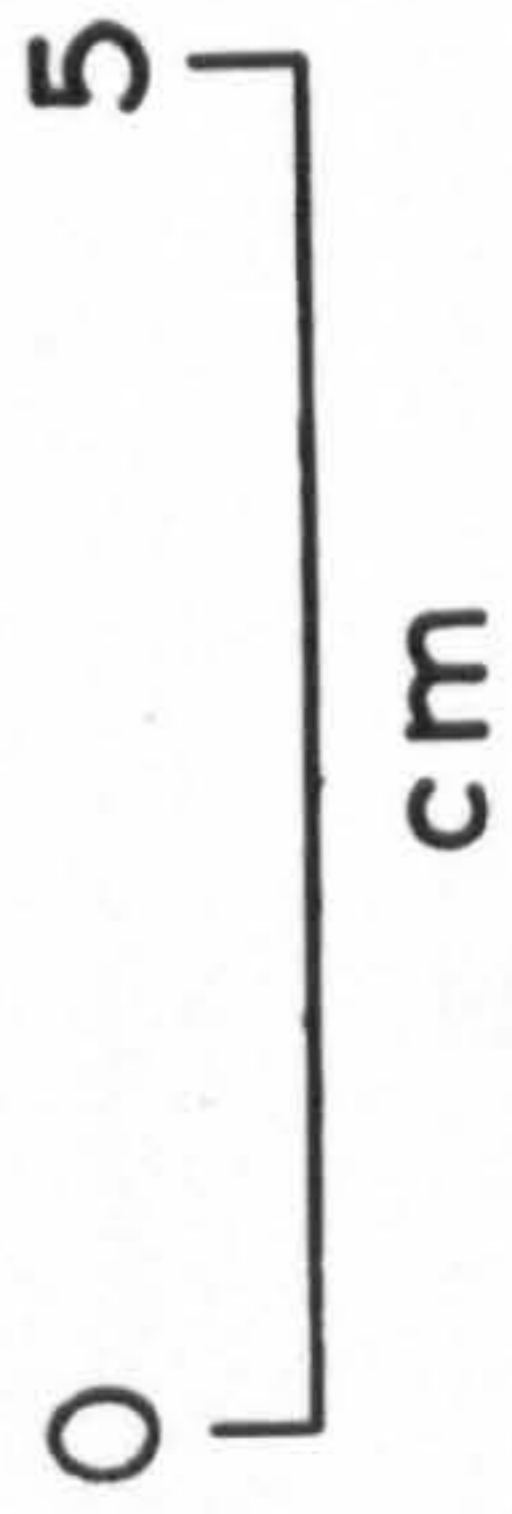
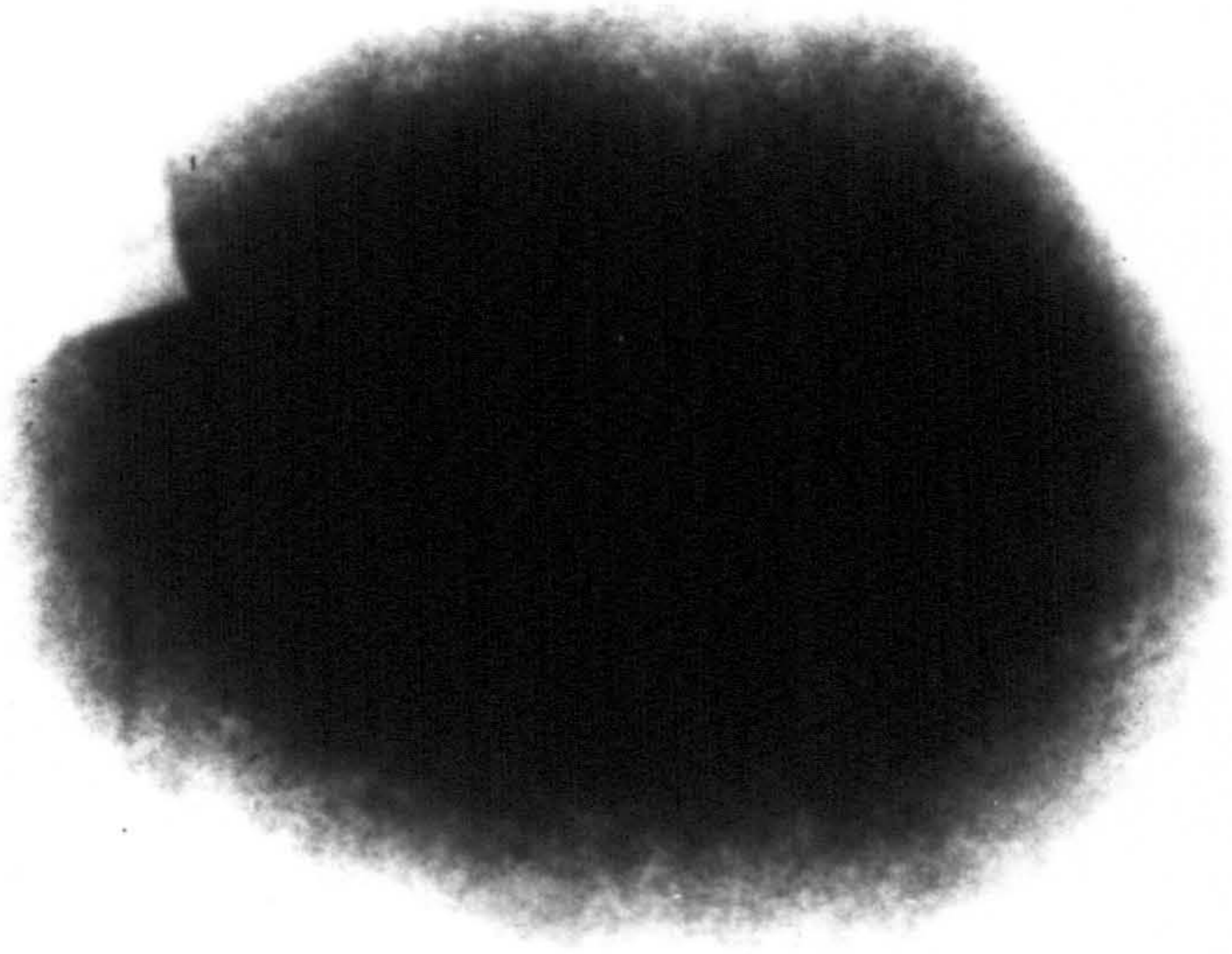
PLATE 5 (b) Intertechnique SL 4000 Liquid Scintillation Counter.



OVERLEAF.

PLATE 6 (a) Initial autoradiograph.

PLATE 6 (b) Second autoradiograph.



OVERLEAF.

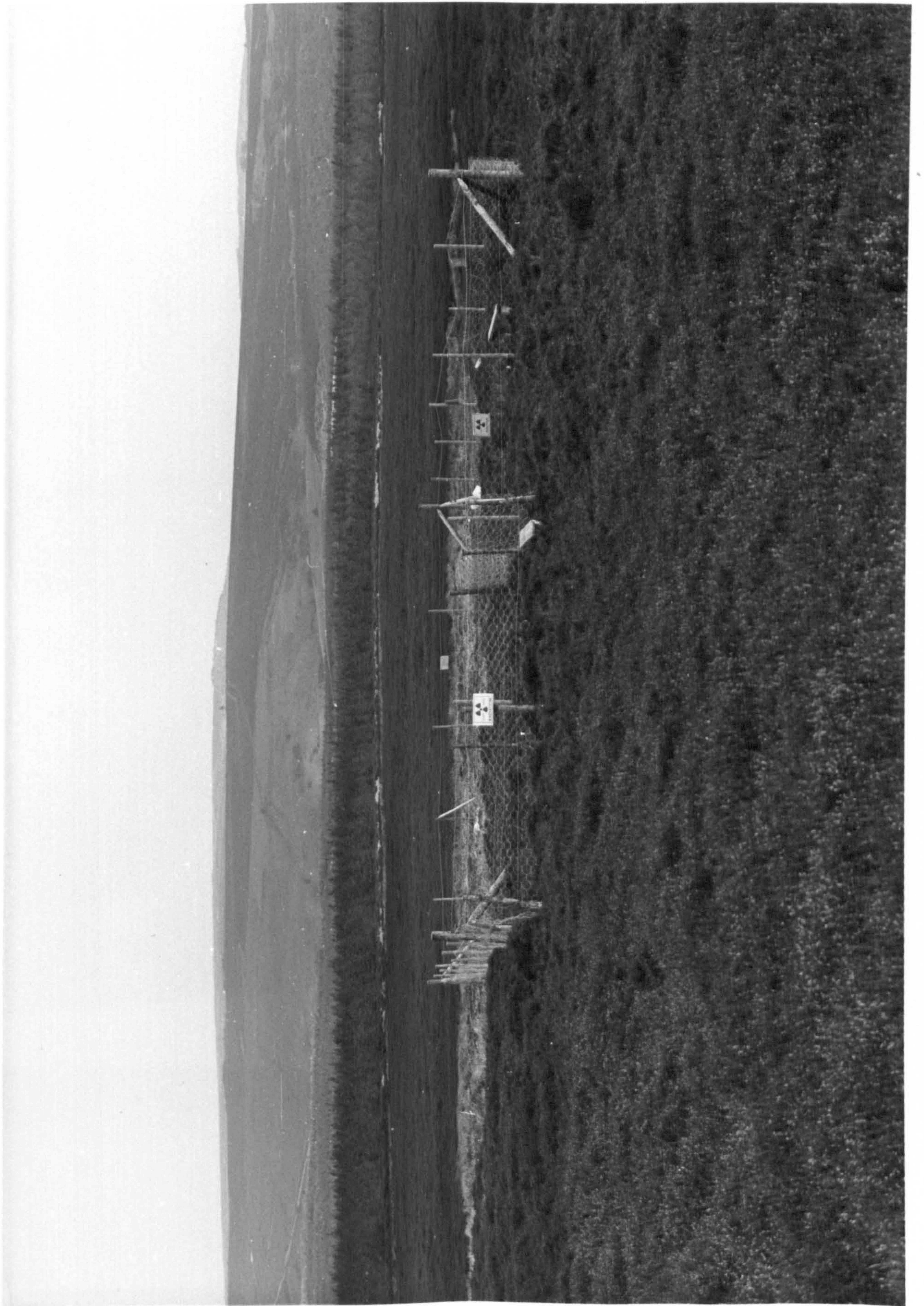
PLATE 7 (a) Sneaton High Moor : vegetated plot.

PLATE 7 (b) Sneaton High Moor : burnt plot.



OVERLEAF.

PLATE 8 General view of Sneaton High Moor plots.



OVERLEAF.

PLATE 9 (a) Vegetation cover on Sneaton High Moor.

PLATE 9 (b) Sneaton High Moor muirburn.



OVERLEAF.

PLATE 10 Sneaton High Moor Automatic Weather Station.



OVERLEAF.

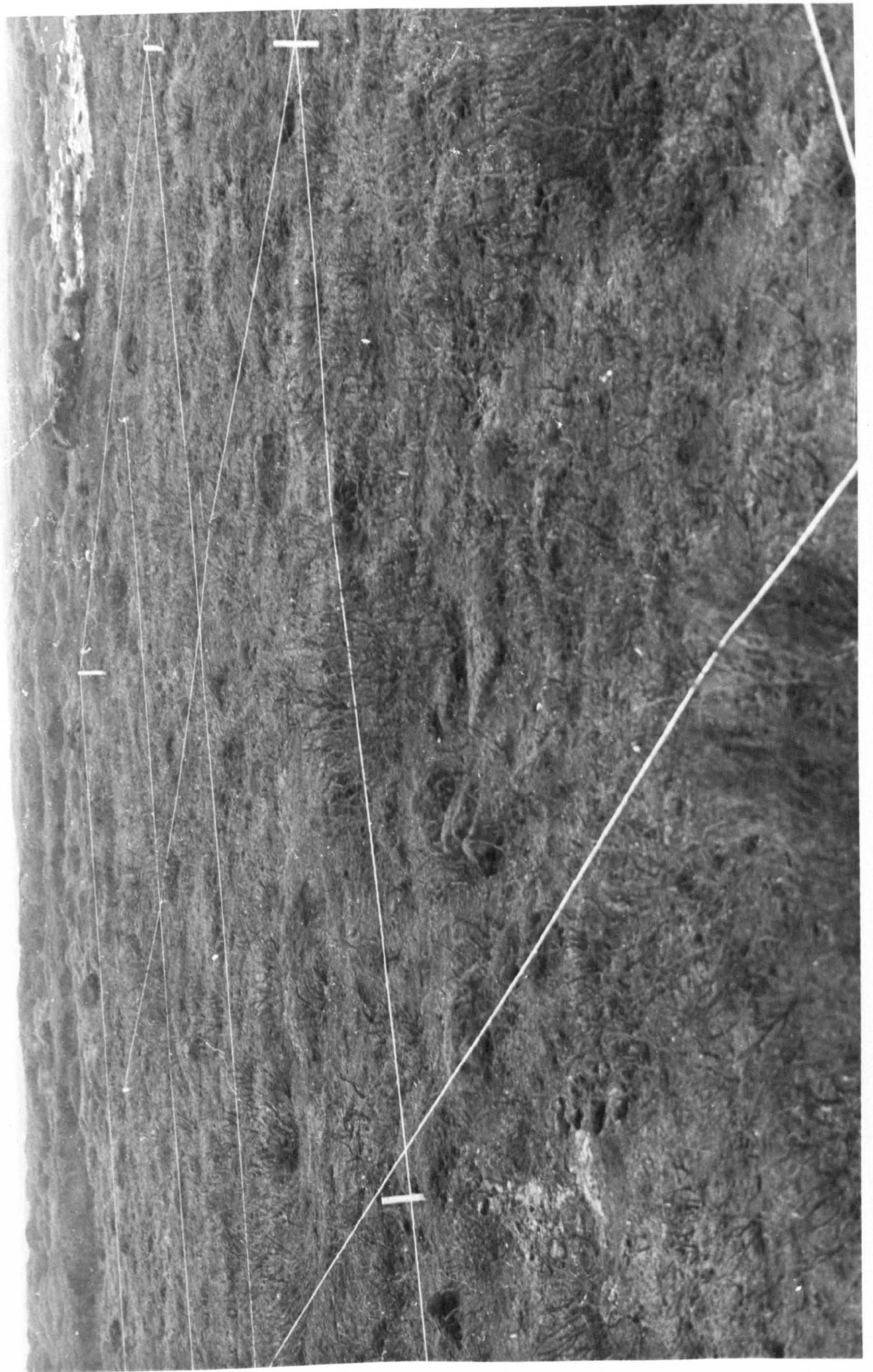
PLATE 11 (a) Egton High Moor muirburn (April 7, 1978).

PLATE 11 (b) Egton High Moor muirburn (April 24, 1978).



OVERLEAF.

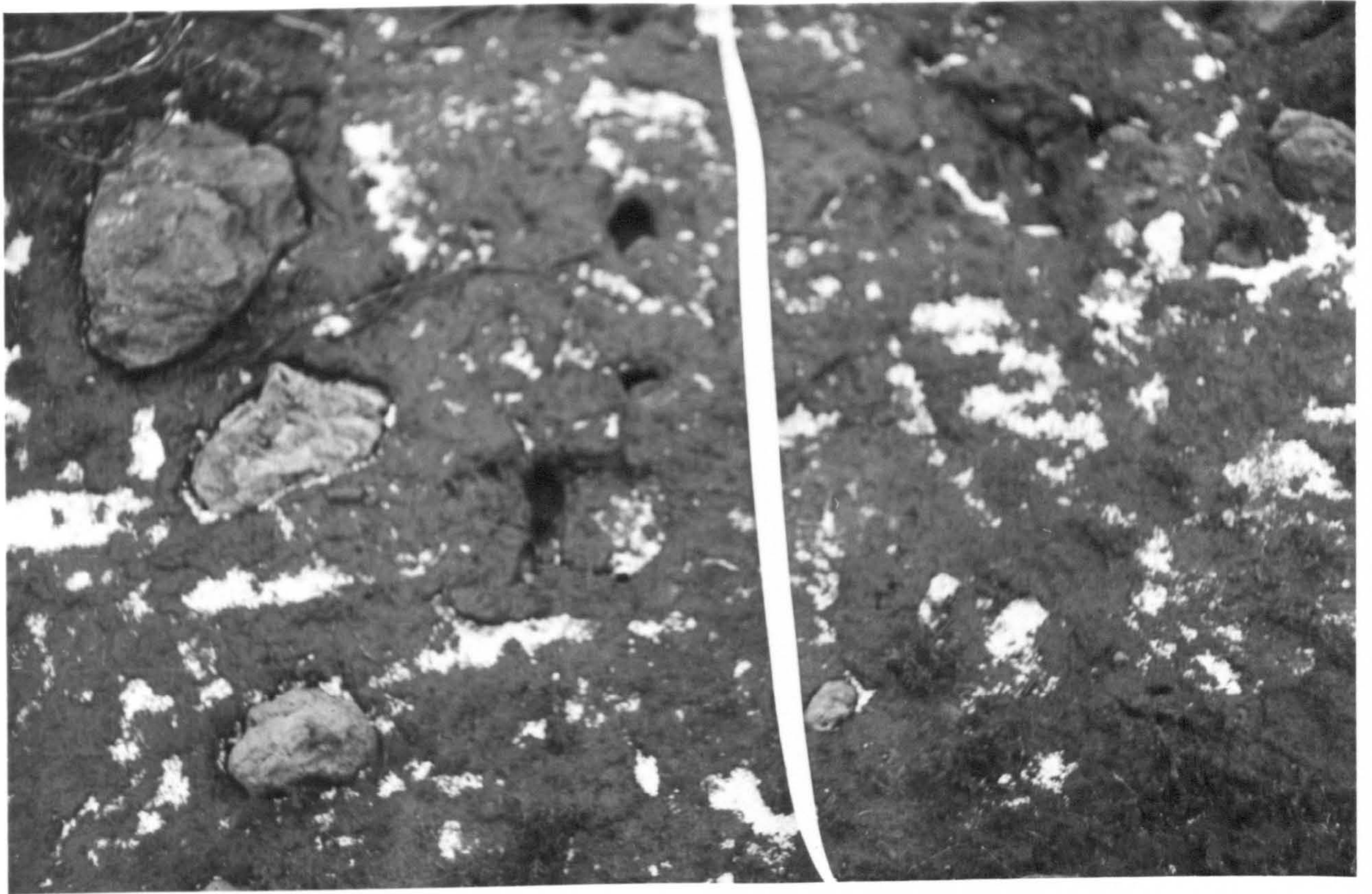
PLATE 12 Intensively burnt plot.



OVERLEAF.

PLATE 13 (a) Frost heave on moderately burnt plot.

PLATE 13 (b) Desiccation cracks on moderately burnt plot.



CHAPTER 6

THE HYDROLOGY OF WINTERGILL CATCHMENT

Introduction

Various aspects of the hydrology of Wintergill catchment are described and analysed in this chapter. This is not a complete account of hydrological transfers and storages within the catchment, but considers specific components of the hydrological system, including precipitation inputs and stream discharge outputs. Description of runoff characteristics forms a necessary precursor to the analysis of sediment discharge in Chapter 7.

Analysis is based upon data collected between April 1, 1978 and March 31, 1979. Initial consideration is given to precipitation as the major hydrological input to the catchment. Then the characteristics of hydrological output, in the form of stream discharge, are examined and attempts made to model the relationships between the two variables. However, a number of environmental factors affects this relationship and their evaluation permits the development of a complex conceptual model for the hydrology of Callunetum moorland.

Precipitation

Measurement of precipitation within the catchment posed a number of problems. The most complete data are available from the check gauge, for which 334 days of data are available, equivalent to 91.5% of the year. Missing data are mainly due to human and animal interference. Additional problems were encountered with the autographic gauge with wintry conditions preventing data collection for a continuous 88 day period. In total, 190 days of data were

recorded by the autographic gauge.

To estimate missing data reference was made to adjacent Yorkshire Water Authority (Y.W.A.) gauges. Autographic precipitation data were correlated against those from four adjacent Y.W.A. gauges. The strongest correlation was with the Westerdale rain gauge (G.R. NZ 664 052) ($r = 0.66$, $P = < 0.001$, $N = 126$), which lies some 6 miles to the north-east of Wintergill. Thus, precipitation was predicted using the regression equation :-

6(1)

$$Y = 0.366934 + 0.77985 (X)$$

where $X =$ Daily precipitation total at Westerdale (mm).

$Y =$ Daily precipitation total at Wintergill (mm).

This equation was used when no data from Wintergill catchment were available. Total precipitation collected by the check gauge between April 1, 1978 and March 31, 1979 was 835.9 mm. Precipitation on the 31 missing days was predicted using either autographic data or the regression equation. Total estimated precipitation during the days of missing data was 131.5 mm giving an estimated total of 967.4 mm. Since no gauge was previously installed within Wintergill catchment one cannot be conclusive as to the comparability of the precipitation total with previous years. The mean annual total (1941-70) for Westerdale is 930 mm which is very similar to the measured Wintergill total.

Monthly precipitation values were estimated as a percentage of the mean monthly value for Westerdale. To calculate daily precipitation values the daily total was predicted from the regression equation. Due to errors in estimation the autographic total plus predicted

total is considerably less than that estimated from the check gauge data. Autographic and predicted precipitation over the year is 873.7 mm. Thus, comparison of the data includes a certain amount of inaccuracy. However, on a relative basis July, December and March were months during which relatively high precipitation totals were received, while October was relatively dry (Table 8, Fig. 12a).

Autographic data was extracted from the weekly charts providing the amount and duration of rain events, from which were calculated mean intensity (mm hr^{-1}), maximum intensity (mm hr^{-1}) and the duration of maximum intensity (hours). To reduce inaccuracies the autographic data were adjusted to the check gauge value and when more than one week's data were available for any particular month some of the mean precipitation characteristics were calculated (Table 8).

DISCHARGE

Streamflow charts recorded stream stage for 295 days of the year. A total of 70 days of data were lost, 11 during late July - early August due to recorder malfunction and 59 consecutive days in Winter due to lack of access.

Stream discharge was highly ephemeral with 96 days of zero flow being recorded. The most prolonged continuous period was during October-November with 35 days without streamflow.

During Winter the catchment area was often covered with frozen snow. However, since the stilling well was frozen, stage was still recorded despite zero discharge. Temperature recordings from the Egton Moor soil plots were examined for days on which

temperature did not rise above 0°C and these were used as a surrogate for temperature conditions within the catchment.

Flow charts for continuously sub-zero days were examined for signs of changes in discharge. On 23 days temperatures were sub-zero but there was evidence of flow. During the intense freeze in January only 3 days provided any evidence of flow. Thus, other days have been interpreted as days of zero discharge. Consequently, many days of missing data are days of nil streamflow.

According to the temperature data, sub-zero conditions were continuous from January 10 to February 15, after which the temperature recorder stopped. Hence, one might assume no flow during this time. However, within the 21 day period between February 15 and March 9, stream discharge did occur. After March 9 streamflow records were again collected. However, the hydrographs resulting from snowmelt during the period February 15 and March 9 were not recorded. The movement of the recorder pen by spring floods allows an estimate of peak discharge during spring floods of $15.269 \text{ l sec}^{-1}$.

A total of 191 days of actual stream discharge were recorded. Very low discharges were recorded for most of the year. Fig. 13 shows the flow duration curve for mean daily discharge, calculated from the 24 hourly discharge values.

Baseflow was variable, but generally less than 0.1 l sec^{-1} , usually in the range 0.05 to 0.07 l sec^{-1} . The flow duration curve shows that mean daily discharge was less than 1 l sec^{-1} for over 85% of the year.

TABLE 8
Precipitation and Runoff Characteristics of Wintergill Catchment

VARIABLE	APRIL	MAY	JUNE	JULY	AUGUST	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MARCH	TOTAL/MEAN
Estimate precipitation total	49.9	43.0	39.8	140.9	75.2	61.4	24.4	47.7	198.3	82.97	18.27	91.80	873.68
Precipitation actually measured (mm)	49.9	41.1	33.0	29.4	29.1	32.2	24.4	37.1	92.3	0	0	37.8	406.3
Mean total for Westerdale (1941-70)	59	63	64	75	101	76	77	113	87	85	74	61	930
% of long term average for Westerdale	84.6	68.2	62.2	187.9	74.5	80.8	31.7	42.21	227.9	97.61	24.69	156	93.94
Mean duration of precipitation events (hrs)	7.83	-	5.06	3.75	5.65	4.43	4.81	8.86	14.93	-	-	-	4.35
Mean intensity of precipitation events (mm hr ⁻¹)	0.308	-	1.05	1.66	0.73	1.27	0.53	0.79	0.69	-	-	-	0.75
Mean maximum intensity of precipitation events (mm hr ⁻¹)	1.15	-	2.45	3.93	1.43	1.38	0.81	0.57	2.85	-	-	-	1.44
Mean duration of maximum intensity (hrs)	2.23	-	0.65	1.13	1.58	2.07	1.27	4.75	3.71	-	-	-	2.30
Estimated runoff (mm)	12.75	27.22	3.27	14.45	29.39	12.34	8.40	7.05	65.69	13.86	12.46	140.30	347.05
Estimated runoff as % of estimated precipitation	25.55	63.28	8.22	10.25	39.08	19.93	34.43	14.78	33.13	16.70	68.03	152.83	

Stormflow was a regular occurrence with 12 distinct flood hydrographs being recorded. Although discharge was low, in absolute terms, storm events produced large relative increases. Maximum discharge was recorded on May 5, 1978, peaking at 15.979 $l\ sec^{-1}$. Hence, maximum stormflow was some 228 times baseflow.

Storms did not produce immediate responses in stream discharge. In each case a time-lag occurred between the beginning of the precipitation event and flood discharge. Autographic precipitation data are only available for four of the storm events. Each flood hydrograph is associated with a distinct storm event. Hence, the time-delay between the commencement of the storm and a rise in stream stage may be estimated by comparing the autographic gauge and stage recorder data. The time-delay between the beginning of the storm and the first signs of stream stage rising were calculated. Time-delay ranged between 4.5 and 9 hours, with a mean of 6.6 hours.

Visual observations of the catchment during stormflow suggests that discharge from the rills forms an important component of stormflow. Two rills in particular (Rill B and C referred to in Chapter 7) generated most runoff. Although Rills A and D were relatively deep (about 20 cm) little flow was generated from them, and one might suggest that they are relict features from a more erosive regime, possibly from a previous burning cycle. Pipeflow was also observed during storm events. Observations from soil pits suggest that interflow above the clay base may be an important component of delayed-flow, as suggested by the rapid filling of pits with water when the base of the Oh horizon was approached.

Storm hydrographs were characterised by very rapid rises in discharge. The rising limb had a mean duration of 8.92 hours. Seasonal differences were observed in the time duration of rising stage. During the six floods recorded between May and October rising stage time was between 1 and 5 hours, with a mean of 3 hours. Rising limbs of the six Winter (November to March) floods were much more prolonged, ranging from 7 to 19 hours, with a mean of 15.2 hours, some 1.7 times longer than summer floods.

The recession limbs of the hydrographs were more prolonged and less steep, although it is not always possible to define when the flood had passed as stages rarely returned to pre-flood levels. Furthermore, the distinction between baseflow and stormflow is often complex with regard to the frequent occurrence of composite storm hydrographs. The quickflow/ delayed flow separation method suggested by Hewlett and Hibert (1967), based on a projected slope of $0.05 \text{ cusecs sec}^{-1} \text{ mile}^2 \text{ hr}^{-1}$ from the base of the storm hydrograph, was not considered applicable to the Wintergill hydrographs, as it is an empirically derived slope based on observations within forested Appalachian watersheds.

Three floods in June 1978 recorded a rise in stage from zero to peakflow followed by recession to zero. Thus, complete hydrographs were defined. In each case the rise from zero to flood peak occurred within one hour. Recession varied between 21 and 49 hours, with a mean of 36 hours. Hence, recession time took some 36 times rising time.

Stream discharge characteristics accord with those reported for streams in similar environments. Tallis (1973) noted ephemeral discharge within a Peak District gully, while Weyman (1974)

observed similar "flashy" hydrograph shapes to those recorded at Wintergill, within a heather-covered catchment in the Mendip Hills.

HYDROMETEOROLOGICAL RELATIONSHIPS

The hydrometeorological variables are inter-related with varying degrees of significance (Table 9). Correlation coefficients are high within the meteorological variables whereas correlations between the meteorological inputs and discharge are more complex.

A significant association is found between total measured weekly precipitation and total stream discharge ($r = 0.71$, $P = <0.001$, $N = 25$). The relationship may be given by the equation :-

6(2)

$$Q = -92.1184 + 28.351 (P)$$

where $Q =$ volume of stream discharge (m^3)

$P =$ precipitation (mm).

The negative intercept value suggests that a precipitation amount of 3.25 mm per week is necessary for streamflow generation. The 50.1% level of explanation offered by the equation is reduced if one considers the correlation coefficients on a daily basis.

The correlation coefficient between daily precipitation and mean daily discharge is maximised by correlating discharge with the Log_{10} of precipitation ($r = 0.33$, $N = 49$, $P = 0.010$). The relationship may be given by the equation :-

6(3)

$$Q = 0.650 + 0.667 (P \text{ Log}_{10})$$

where $Q =$ mean daily discharge ($l \text{ sec}^{-1}$)

$P =$ daily precipitation (mm).

TABLE 9

Correlation Coefficients Between Hydrometeorological Variables

	Sign. at 0.05 confidence level		Sign. at 0.001 confidence level	
Precipitation amount (mm)	<u>0.75</u> N = 189			
Duration of precipitation (hrs)				
Mean intensity of precipitation (mm hr ⁻¹)	<u>0.41</u> N = 189	<u>0.24</u> N = 189	<u>0.28</u> N = 189	
Maximum precipitation intensity (mm hr ⁻¹)	<u>0.63</u> N = 189	<u>-0.19</u> N = 189	<u>0.15</u> N = 189	<u>-0.29</u> N = 189
Duration of maximum precipitation intensity (hrs)	<u>0.30</u> N = 189	<u>0.55</u> N = 189	<u>0.08</u> N = 186	<u>0.07</u> N = 186
Mean daily discharge (l sec ⁻¹)	<u>0.23</u> N = 187	<u>0.21</u> N = 189		
	Precipitation amount (mm)	Duration of precipitation (hrs)	Mean intensity of ppte (mm hr ⁻¹)	Max. precipitation intensity (mm hr ⁻¹)
				Duration of max. precipitation intensity (hrs)
				Mean daily discharge (l sec ⁻¹)

TABLE 10
Minimum Contributing Area for Selected Floods

RAINFALL CHARACTERISTICS	DATE OF FLOOD		
	April 26, 1978	June 7, 1978	December 27, 1978
Est. Rainfall (I) mm ³	1616.5 x 10 ⁶	451.2 x 10 ⁶	2310.52 x 10 ⁶
Est. runoff (O) ml	480.71 x 10 ⁶	145.86 x 10 ⁶	354.01 x 10 ⁶
O/I (1)	0.29746	0.32327	0.15321
I1 - O1 m ³ (2)	1135.79	305.34	1956.5
C min 1 (%)	29.75	32.33	15.321
Estimated area of C (m ²)	13,980.99	15,193.87	7,202.79
O/A storm runoff (mm) (3)	0.0102	0.0031	0.0075

Indices based on those of Weyman (1974)

- (1) O/I = Proportion of storm rainfall that becomes storm runoff
- (2) I-O = Loss due to infiltration
- (3) O/A = Storm runoff (mm)

Explanation of variance offered by the equation is low, at 10.9%. Hence, there is a great deal of scatter about the regression line (Fig.14).

The strength of correlation between mean daily discharge and the duration of the precipitation event was maximised by correlating discharge (Log_{10}) with duration (Log_{10}), ($r = 0.25$, $N = 48$, $P = 0.042$). The relationship is given by the equation :-

6(4)

$$Q = 1.107 D^{0.51171}$$

where $D =$ Duration of the precipitation event (hrs).

Again explanation of variance is low, at 6.35%. Correlations between the dependent variable discharge and the independent variables mean precipitation intensity (M) and duration of maximum intensity (Du) were observed. The respective correlation coefficients are $r = 0.22$ ($N = 105$, $P = 0.02$) between discharge and mean precipitation intensity and $r = 0.18$ ($N = 105$, $P = 0.093$) between discharge (Log_{10}) and the duration of maximum intensity. The relationships can be given by the following equations :-

6(5)

$$Q = 0.464 (M) + 0.476$$

where $M =$ Mean precipitation intensity (hours)

Explanation of variance = 4.02%.

6(6)

$$(\text{Log}_{10}) = 0.102 (Du) - 0.981$$

where $Du =$ Duration of maximum precipitation intensity (hours)

Explanation of variance = 3.25%

The calculation of partial correlation coefficients reveals no further significant correlations between the meteorological variables and stream discharge. Attempts to improve the level of stream discharge variance which is explained by the meteorological variables by multiple regression proved unsuccessful. Partly due to problems of data transformation, in that the variables could not be in both linear and logarithmic form, within the equations, the explanation of variance offered could be little improved. Thus, the single variable, precipitation amount, is the best predictor of stream discharge.

The low explanation of variance in stream discharge offered by the meteorological variables may be due to the complexity of the hydrological system. Numerous variables will affect the hydrometeorological relationships and four major influences are given further consideration. These are the internal complexity of the Callunetum hydrological system, the influence of partial area hydrology, and the affects of seasonal influences and antecedent moisture conditions.

The internal complexity of water movement within the catchment

Empirical rainfall runoff relationships represent a 'black-box' situation (Ward, 1971), in which inputs and outputs to the system are known, but where hydrological transfers are difficult to define. Not all the water entering the catchment as precipitation is released as stream discharge. Over the year total rainfall, using measured and predicted data was 967.4 mm and total measured runoff from the 4.7 ha catchment was 311.53 mm. Using the regression analysis, discharge was predicted from precipitation data for days on which actual stream discharge was not recorded.

Predicted runoff was 53.39 mm for the 35 day period. Hence, total runoff of 364.92 mm represents 37.72% of total precipitation.

Compared with other reported data the precipitation runoff value represents a relatively small proportion of water released from the catchment. Cryer (1976) found that 82.1% of precipitation was released as discharge over an annual cycle within a small upland catchment in Wales. Smith (1965) found the corresponding value over a 23 year period of record to be 72% within an upland Pennine catchment.

The Wintergill value accords more closely with lowland catchments. Imeson and Ward (1972) report annual percentage precipitation evacuated as runoff to be 34.3, 27.9 and 49.3% for the respective years 1966 to 1969, within a lowland agricultural catchment in Holderness. Walling (1974) reports annual evacuation rates of 45 and 42.9% in small agricultural catchments in Devon while the Wintergill value is lower than the 49% reported for a small forested catchment in Luxembourg (Verstraten, 1977). The low evacuation rate from Wintergill is akin to the low evacuation rates associated with south and east England (Ward, 1968).

Since only some 38% of precipitation entering the catchment was released as stream discharge, the moisture must be retained within the system, or released through other hydrological routes. Such factors as interception, transpiration, water retention by the biomass and soil and sub-surface seepage will influence the movement of water within the catchment.

Initial absorption of precipitation will be due to vegetation interception. Leyton et al (1967) report that 33 to 66% of

rainfall is intercepted within a heather canopy, but rates are highly variable depending on a number of factors. According to Barclay-Estrup (1971) interception varies throughout the Callunetum growth cycle ranging from 29.2% in the pioneer growth phase, to 54.04% in the mature community.

Interception rates vary in response to rainfall conditions. According to Aranda and Coutts (1963) precipitation less than 0.04 mm hr^{-1} will not penetrate the Calluna canopy while interception rates normally decrease during more prolonged and intense precipitation. Thus, only a mean of 14.5% ($\pm 6.1\%$, $N = 26$) of recorded precipitation penetrated the experimental stand in Aberdeenshire when total precipitation was less than 10 mm and less than 3 mm hr^{-1} in intensity. With increasing intensity and duration penetration increases. With a precipitation total of more than 15 mm and an intensity greater than 5 mm hr^{-1} , 62.8% ($\pm 13.1\%$, $N = 9$) of precipitation penetrated the canopy. Consequently, interception is significant in the absorption of precipitation, thus decreasing potential water for runoff.

Transpiration forms a hydrological route whereby water may leave the catchment without becoming streamflow. Transpiration rates vary throughout the annual cycle. Experiments by the Institute of Hydrology have measured a mean daily transpiration rate of 2.3 mm day^{-1} during June-July 1979, from Callunetum stands on Sneaton High Moor (J. Roberts, pers. comm.), and such a rate extrapolates to $23.3 \text{ t ha}^{-1} \text{ day}^{-1}$, or 97.63 t day^{-1} for the mature, vegetated area of Wintergill. Transpiration rates are considerably less in Winter, with a mean of 0.1 mm day^{-1} .

Evaporation is an important hydrological transfer in heather

moorland. Daily Penman estimates of evaporation were made on Sneaton High Moor, using the Didcot Automatic Weather Station data (Plate 10). Evaporation was estimated using the equation given by Penman (1953).

6(7)

$$E_r = \frac{\Delta H + E_a}{\Delta + \gamma}$$

where E_r = Evaporation from vegetated surface (mm)

H = Heat Balance

E_a = Saturation vapour pressure at mean air temperature of vegetated surface

Δ = Slope of the saturation vapour pressure curve against mean air temperature in mm Hg per °F

γ = Psychometric constant

Over a 272 day period of record between August 1979 and June 1980 the daily Penman estimate of evaporation varied between 5.07 and -0.28 mm, with a mean of 1.06 mm. Total estimated evaporation was 287.23 mm, which, assuming the mean to be representative, extrapolates to 385.44 mm yr⁻¹. This is probably an underestimate due to the greater number of Winter values contributing to the mean and data gaps in the Summer record. Nevertheless, the data do indicate that in excess of one-third of annual precipitation totals may be lost from the heather moorlands by evaporation, hence reducing the supply as runoff.

The heather biomass may absorb and retain large volumes of water and some estimates of moisture content were made. A total of eight 0.5 m² samples of heather and litter were taken, 4 from the Egton High Moor plots in April 1978 and 4 from Sneaton High Moor plots in November 1978. For the 8 samples the moisture

content of heather varied between 8.3% and 47.6%, while the biomass ranged between $415 \text{ g } 0.5 \text{ m}^{-2}$ and $1255 \text{ g } 0.5 \text{ m}^{-2}$. For the litter samples moisture content ranged from 48.4% to 64.3%. Mean heather biomass for the 8 samples was $967.5 \text{ g } 0.5 \text{ m}^{-2}$ with a moisture content of 36.4%, the equivalent figures for litter being $240.5 \text{ g } 0.5 \text{ m}^{-2}$ and 60.3%

Extrapolating the moisture content and biomass values would produce a vegetation moisture content of 14.095 t ha^{-1} contained in the heather and 5.81 t ha^{-1} contained within the heather litter. Total moisture content would be 19.9 t ha^{-1} . In terms of the mature vegetated catchment area these results would extrapolate to 83.4 t .

These data only refer to a small sample, and moisture contents will be dynamic, both in terms of vegetation characteristics and through time. Nevertheless, the data do suggest that large volumes of water may be retained and conserved within the Callunetum ecosystem, thus diminishing the potential supply as runoff.

The catchment soils can apparently retain and absorb considerable quantities of water. Peaty soils have a high moisture capacity, as discussed by Boetler (1966), with reference to peats in the U.S.A., and by Dasberg and Neuman (1977) examining the peats of the Hula Basin in Israel. The moisture retaining properties of peaty gley soils are discussed in more detail in Chapter 8, although the Egton Moor soils moisture content in the upper 10 cm was found to vary between 12.7 and 59.4% with a mean figure of 37.9% (N = 39). The samples were taken in Spring and Autumn.

To calculate the mass involved a soil block was removed adjacent to the sampling plots. The block was 0.25 m^2 in area and 10 cm deep, with a dry-weight of 2.043 Kg. Assuming the weight of the block to be representative, a moisture content of 37.9% would extrapolate to 6.21 Kg m^{-2} or 62.02 t ha^{-1} . Such a value is 3.12 times the estimated moisture content of the vegetation. Further extrapolation to the catchment area would indicate a top soil moisture content of 291.5 t.

Deep, sub-surface seepage may contribute to water loss but this factor is not considered to be of major significance within Wintergill, as the catchment is underlain by clay at a depth of some 0.4 m (Chapter 2). From observations in soil pits and road cuttings, seepage occurs at the O/A horizon interface, but as this boundary is intersected by the road cutting, it would appear that all interflow is directed into the stream channel.

The preceding discussion emphasizes that mature Callunetum moorland is able to conserve moisture within the ecosystem. Thus, water entering the catchment may be retained or leave the catchment by a variety of routes, apart from stream runoff. While the hydrological routes considered are complex and variable in their efficiency through the annual cycle, they allow an explanation of the relatively small proportion of water input which leaves the catchment as stream discharge.

The Influence of Partial Area Hydrology

The runoff process itself is also complex. Several workers provide evidence that the contribution of catchment area to discharge is neither uniform nor consistent. Based upon investigations of small catchments in Ohio, Amerman (1965) suggests

that catchment areas greater than approximately 1.2 ha are physically complex and composed of a number of "unit source areas", each possessing different hydrological characteristics. The heterogeneity of small catchments is stressed by Sharma et al (1980), demonstrating the variation in soil infiltration properties within a 9.6 ha Oklahoma catchment.

Empirical observations have furthered the development of the partial area concept. Thus, runoff is preferentially generated by specific source areas. Betson (1964) found that the actual area actually contributing to discharge ranged from 4.6% to 85.8% of the catchment area in a number of Tennessee basins. Furthermore, contributing area is variable through time, as demonstrated by Dunne and Black (1970) within a small catchment in Vermont, U.S.A., and by Nakumara (1971) in Japan. Thus, a fuller understanding of the complexity of Callunetum moorland hydrology requires some consideration of partial area contributions.

Discharge from Wintergill is not generated uniformly within the catchment. An estimated total of 14,691.92 m³ of streamflow was measured over the 'V' notch weir, and such runoff would require the generation of 0.31153 m³/m²/yr or 311.53 mm/m²/yr of runoff from the catchment area. However, contribution from the catchment is not uniform. Estimates were made of the area contributing to stormflow, using the procedures described by Weyman (1974) and Finlayson (1977). The formula for minimum contributing area assumes that

"... 100% of rainfall over that area becomes storm runoff, with no loss to soil moisture."

(Weyman, 1974). The formula is :-

6(8)

$$C \text{ min} = \frac{O}{I} \times 100\%$$

where $C \text{ min}$ = Minimum contributing area (%)

O = Estimated storm runoff (ml)

I = Total storm rainfall (ml)

Using this equation, the minimum contributing area was calculated for 3 storms for which the flood hydrographs are well defined and precipitation data are available (Table 10). The results demonstrate that minimum contributing areas are a relatively small and variable portion of the catchment area, ranging from 15.3 to 32.3%.

Weyman (1974) and Finlayson (1977) both report that minimum contributing area are variable. The 0.11 Km² experimental catchment of East Twin Brook, Somerset, which is environmentally similar to Wintergill, has a minimum area contributing to stormflow of between 0 and 77% of catchment area. Visual inspection of Wintergill during runoff events revealed that most discharge issued from the rills, described in Chapter 2. Runoff movement within the catchment is further complicated by additional factors, apart from the influence of partial area contributions. Weyman (1974) considers overland flow to be an important component of water movement through peaty soils, due to the low infiltration capacity of the A₀ horizon. Overland flow, therefore, will be preferentially generated from such unit-source areas.

Water may also move through the catchment as sub-surface flow. Theoretically, the transmission of water through peat as throughflow is in accordance with Darcy's Law, whereby the volumetric flux (Q) is proportional to the loss of hydraulic head

(ΔH) and inversely proportional to the distance through which the water has passed (ΔL). The equation may be given as :-

6(9)

$$Q = -K \frac{\Delta H}{\Delta L}$$

Rycroft et al (1975) report that Darcy's Law is applicable to peats of low humification, based on field investigations in a Perthshire catchment. However, many factors influence water transmission. Hydraulic conductivity decreases with increasing overburden pressure, bulk density and substance volume. Thus, Rycroft et al report rates of hydraulic conductivity ranging between 10^2 to 10^{-8} cm sec⁻¹. Ingram et al (1974), in a three year investigation of the same Perthshire catchment, found that, overall, Darcy's Law was largely inapplicable.

Rapid transmission of water through peaty soils occurs within soil pipes, which occur frequently within upland environments (Jones, 1971) and have been observed within Wintergill. Hence, the influence of these various factors affecting water transmission through peaty soils, may be offered as a partial explanation for the small proportion of stream discharge variance explained by precipitation.

The influence of season on hydrometeorological relationships

The hydrological characteristics of Wintergill catchment are not constant throughout the annual cycle. Seasonal differences are evident in the rainfall-runoff and the hydrometeorological relationships, in particular those between precipitation input and stream discharge. Temporal variations in the rainfall-runoff relationships are demonstrated in Fig. 12a and Table 8, but the

results should be examined cautiously due to missing data. Such gaps necessitated the extrapolation of hydrometeorological data and, as discussed previously, those predictions underestimate precipitation amounts.

Fig. 12b displays a general seasonal trend of the proportions of precipitation leaving the catchment as runoff. The lowest proportions are evacuated in Summer, with a minimum in June, increasing through Autumn and Winter to a peak in Spring. The Spring peak is attributable to snowmelt, releasing water from the catchment which has accumulated during Winter as snow.

To examine seasonal differences, the year was divided into "Summer" (May to October) and "Winter" months (November to April). Analysis of variance was then performed on the variables (Table 11), revealing very different hydrometeorological conditions in the two periods. In Winter, mean daily precipitation amounts and durations are greater than in Summer while the mean duration of maximum intensity is approximately 10 times longer. Mean maximum precipitation intensity is marginally greater in Summer, probably due to local thunderstorms, although the generally greater amounts and intensities in Winter encourage higher runoff totals. Mean daily Winter discharges are over three times higher than their Summer equivalents.

Association analyses examined the relationships amongst Summer hydrometeorological variables, which although being highly intercorrelated, showed no significant relationships with daily discharges. A similar analysis of Winter data revealed similar inter-relationships within the meteorological variables, but significant associations were found between stream discharge and

two of the variables involved. Correlation coefficients of $r = 0.30$ ($P = 0.015$, $N = 54$) and $r = 0.32$ ($P = 0.09$, $N = 54$) were found between stream discharge (Log_{10}) and precipitation amount and duration respectively. Partial correlation did not strengthen these associations although multiple regression marginally increases the variance explained to 10.8%, with the equation :-

6(10)

$$Q (\text{Log}_{10}) = 0.009 (P) + 0.024 (D) - 0.782$$

Multiple $r = 0.33$. $N = 54$.

The Summer data reveals a lack of association between precipitation and runoff, probably due to relatively low precipitation amounts, enhanced soil and biomass storage capacities and increased evapotranspiration rates.

Mean estimated Summer evaporation was 29.2%, compared with 57.3% in Winter, these results comparing favourably with those reported for a lowland agricultural catchment (Imeson and Ward, 1972). Where, over a three year period, mean "Summer" evaporation was 17.5% compared with 59.8% in Winter. Thus during "Summer", water may enter the catchment and leave it by a variety of routes generally excluding runoff. Hydrometeorological conditions in Winter are quite different as precipitation inputs are considerably greater and evapotranspiration is much reduced. Consequently, the response of stream discharge to hydrometeorological inputs is sharpened and significant correlations between these variables occur. Nevertheless the internal complexity of the hydrological systems is such that the rainfall-runoff relationship is far from simple.

Institute of Hydrology evaporation data (J. Roberts, pers. comm.)

confirms greater evaporative losses in Summer as opposed to Winter. Available data collected between May and October (1979 and 1980) reveal Penman daily estimates of evaporation ranging between 5.06 and 0.09 mm, with a mean of 1.83 mm (N = 85). In contrast, data collected over a Winter period (November 1979 to April 1980) varied between 5.07 and -0.28 mm, with a mean of 0.7 mm (N = 187). Thus, mean daily Penman estimates of evaporation in Summer exceed those in Winter by a factor of 2.61.

The relationships imply a threshold in moisture content within the catchment which, if exceeded, results in proportionally greater runoff. Over the year the general relationship between meteorological variables and discharge is of an asymptotic nature. Hence, the catchment appears able to absorb moisture and only release a decreasing proportion with increasing moisture inputs.

Over the Summer period the relationship between input and output is undefinable, presumably as the threshold for direct response is not achieved. Tallis (1975) considers rainfall intensity and duration important in producing runoff response, reporting a value of 0.75 cm precipitation in 24 hours as the critical limit in producing runoff in a Peak District gully. Although there is considerable scatter within the data, the Winter relationship approximates more to an exponential form. An increase in precipitation input tends to produce a disproportionately large increase in stream discharge.

According to the Hortonian Model (Horton, 1933, 1945), critical moisture levels are not achieved until all the hydrological deficits are replenished. When soil, vegetation and evapotranspiration storages are replete, precipitation inputs will produce a direct

TABLE 11
T-test of seasonal differences in hydrometeorological variables

VARIABLE	MEAN SUMMER	MEAN WINTER	T VALUE	D.F.	SIGNIFICANCE
Daily precipitation amount (mm)	1.69	3.59	-1.81	40	0.078
Precipitation duration (hrs)	1.87	7.02	-4.12	40	<0.001
Mean precipitation intensity (mm hr ⁻¹)	0.38	0.42	-0.16	40	0.877
Maximum precipitation intensity (mm hr ⁻¹)	0.91	0.81	-0.28	40	0.105
Duration of maximum precipitation intensity (mm hr ⁻¹)	0.25	2.42	-4.15	40	<0.001
Stream discharge (l sec ⁻¹)	0.2378	0.6984	-3.98	40	<0.001

TABLE 12

T-test of differences in hydrometeorological conditions
in relation to antecedent precipitation

VARIABLE	MEAN NO PPTNE PREVIOUS 24 HOURS	MEAN PRECIPITATION PREVIOUS 24 HOURS	T VALUE	D.F.	SIGNIFICANCE
Daily precipitation amount (mm)	0.937	3.2025	-2.98	167	0.008
Precipitation duration (hrs)	1.186	5.739	-5.77	166	<0.001
Mean precipitation intensity (mm hr ⁻¹)	0.189	0.508	-2.58	166	0.022
Maximum precipitation intensity (mm hr ⁻¹)	0.301	0.964	-3.65	166	<0.001
Duration of maximum precipitation intensity (mm hr ⁻¹)	3.235	1.787	-0.97	166	0.236
Stream discharge (l sec ⁻¹)	0.1987	0.88	-2.88	167	0.005

runoff response, albeit complicated by the effects of partial area hydrology. However, runoff will tend towards an exponential increase with increasing input as the catchment approaches saturation. Evidence tends to be exceeded in 'Winter' rather than 'Summer' and consequently, the hydrometeorological relationship approximates an exponential form.

The influence of antecedent precipitation on hydrometeorological relationships

Discussion has previously implied that antecedent moisture conditions influence hydrometeorological relationships within Wintergill catchment, in particular the tendency for an exponential increase in stream discharge with precipitation input in Winter.

An attempt was made to examine the effects of antecedent precipitation on stream discharge. Data were divided into two sets, one including days when precipitation occurred within the previous 24 hours, and a second involving no previous rainfalls. The cases in each group were 97 and 72 respectively, although a major problem proved to be the paucity of Winter precipitation information.

Comparing the two data sets (Table 12), the mean of each precipitation variable, with one exception, was significantly different between each group. Mean daily discharge was some 5.2 times higher on days when precipitation had been recorded in the previous 24 hours than on days when no precipitation was recorded.

The relationships were tested by correlation analysis. On days when no precipitation was recorded in the previous 24 hours, negative correlation coefficients were calculated between the dependent variable, stream discharge (Log_{10}) and the independent

variables precipitation amount ($r = -0.18$, $P = 0.039$, $N = 97$), mean precipitation intensity ($r = -0.34$, $P = <0.001$, $N = 97$) and maximum precipitation intensity ($r = -0.21$, $P = 0.030$, $N = 97$). Partial correlation analysis did not increase the levels of association. Thus, the coefficients imply an exponential decrease in stream discharge with precipitation input.

Hydrometeorological relationships during days when precipitation had occurred within the previous 24 hours are quite different. A positive correlation existed between discharge and precipitation total (Log_{10}) ($r = 0.3233$, $P = 0.031$, $N = 31$), suggesting an asymptotic relationship. Neither simple nor partial correlation analyses revealed further significant correlations with discharge.

The data were further analysed using multiple regression and for days with no antecedent precipitation the equation is :-

6(11)

$$Q (\text{Log}_{10}) = -0.039 (P) - 0.203 (Mn) + 0.630 (Mx) - 1.452$$

where $Mn = \text{Mean precipitation intensity (mm hr}^{-1}\text{)}$
 $Mx = \text{Maximum precipitation intensity (mm hr}^{-1}\text{)}$

Multiple $r = 0.24$. $N = 97$.

The variable mean intensity explains 8.48% of variance. Total explanation of variance is 12.77%.

The regression equation for days during which precipitation was recorded within the previous 24 hours may be given as :-

6(12)

$$Q = 0.603 (P_{\text{Log}_{10}}) + 0.737$$

The variable precipitation amount offers more explanation of variance for days on which precipitation had occurred within the previous day and days when it had not, at 10.45% and 3.22%, respectively.

Using these simple equations a precipitation input of 10 mm will produce a predicted mean daily discharge of 1.045 l sec^{-1} when no precipitation had fallen in the previous 24 hours. With antecedent precipitation, however, the predicted runoff is 1.400 l sec^{-1} , 25% higher.

The two-fold division of the data is itself an oversimplification of catchment hydrology. Longer time-lags may persist between precipitation and runoff, with water residence and transmission times dependent on numerous environmental variables. Examination of these delayed responses recommended lag correlation analysis, using the procedures of Ogiwara (1967) and Rao et al (1980), but due to discontinuities in the data such analysis is not considered feasible.

To further investigate the effects of antecedent moisture conditions the Antecedent Precipitation Index (A.P.I.) was calculated, using the procedures of Linsley et al (1949, 1958). The Index incorporates precipitation on the day of record and antecedent precipitation for previous days, the weighting of which decreases logarithmically with increasing antecedence. The A.P.I. equation may be given as :-

6(13)

$$I_t = I_0 K^t$$

where I = Index at day t .

I_0 = Initial value of index, based on :-

$$I_0 = b_1 P_1 + b_2 P_2 + b_3 P_3 + b_t P_t$$

assuming $b_t = K^t$.

K = A recession factor, varying between 0.85 and 0.98).

(A recession factor of 0.9 was used, as recommended by Linsley et al (1958) as applicable to the humid temperate North-eastern U.S.A.)

As a preliminary assessment the Index was calculated for each day and up to 6 antecedent days. Thus the A.P.I. of each day was based upon at least 2 and at most 6 antecedent days. Correlation between mean daily discharge and A.P.I. was significant ($r = 0.39$, $P = < 0.001$, $N = 166$). Calculation of correlation coefficients for each set of antecedent days (i.e. antecedent days 2, 3, 4, 5 and 6) and stream discharge, does suggest that precipitation amounts two to three days antecedent to stream discharge are most strongly associated with stream discharge. Thus $r = 0.76$ ($P = < 0.001$, $N = 12$) between mean daily discharge (Q) and A.P.I. with 3 days of values, which decreases to $r = 0.29$ ($P = < 0.001$, $N = 120$), when 6 days are incorporated into the A.P.I.

To check the result unconverted daily precipitation totals, measured antecedent precipitation over a 6 day period and total precipitation for combinations of these 7 days, were correlated with Q . The strongest association was found between mean daily stream discharge and the sum of precipitation recorded the previous day and the day prior to that ($r = 0.49$, $P = < 0.001$, $N = 123$).

Extension to include all data where 2 days of antecedent data were available slightly improved correlation to $r = 0.50$ ($P = < 0.001$, $N = 166$). Recalculation of the A.P.I. to include only 2 days antecedent data, and subsequent correlation, did not produce a stronger association ($r = 0.38$, $P = < 0.001$, $N = 166$). Thus, the strongest association is found using the regression equation :-

6(14)

$$Q = 0.032 + 0.034 (P_1 + P_2)$$

where $Q = \text{Mean daily discharge (l sec}^{-1}\text{)}$

$P_1 = \text{Precipitation recorded on antecedent day (mm)}$

$P_2 = \text{Precipitation recorded on day antecedent to } P_1 \text{ (mm).}$

The equation improves explanation of variance to 24.2% and does suggest that antecedent catchment wetness does influence stream discharge, and that a lag effect occurs between precipitation and discharge. Thus, the sum of precipitation recorded over the previous 2 days is more important in explaining stream discharge levels than precipitation recorded on the same day.

The result agrees broadly with those reported by Burgess (1976), who found that discharge within Bransdale was most strongly associated with the antecedent day's precipitation, within Upper Hodge Beck, and with precipitation two days prior, within Upper Bloworth Slack.

CONCLUSION

Despite the small size of Wintergill catchment a number of problems remain concerning the hydrology of heather moorland. The multiplicity of environmental variables involved in water movement within the catchment often prevents simple observation of

hydrological phenomena. However the examination of these environmental variables allows the development of a conceptual notion of the complexity of the hydrology of such an upland humid environment.

Meteorological inputs into the catchment and hydrological output are related. Output, as stream discharge, is ephemeral. Long periods of zero or low discharge are interspersed by flood events, involving very rapid rises in stream discharge followed by more gradual recessions. The relatively low stream output as a proportion of precipitation input suggests that the catchment can absorb and retain large volumes of water or release water by transfers other than stream discharge, in the same relative proportions as lowland catchments.

The input-output relationship is a black box approach to hydrological modelling. A number of variables influence hydrological responses within the system. The internal complexity of hydrological throughput is such that inputs are transformed through a variety of routes and storages, further complicated by partial area contributions, seasonal variations and antecedent moisture conditions.

CHAPTER 7

SEDIMENT DISCHARGE FROM WINTERGILL CATCHMENT

Introduction

The hydrology of Wintergill has a significant influence upon the fluvial denudation of the catchment. In this chapter some aspects of fluvial sediment discharge are examined. Firstly, the nature and types of fluvial sediment evacuated from the catchment are discussed and relationships investigated between the sediment load and the hydrological variables. Secondly, using a relationship between fluvial and sediment discharge, total sediment loads are estimated.

The calibration of fluvial and sediment discharge is a recurrent problem in geomorphological process studies. Recently, the possibility of estimating denudation rates using calibrations between stream sediment concentration and turbidity recordings from a photo-electric turbidity meter have been highlighted (Imeson, 1977; Walling, 1977, 1978). However this approach was not adopted due to the unavailability of such instruments, and the problem of algal growths on turbidity cells still poses a problem (J. Ellis, pers. comm.).

A more traditional approach has been the construction of sediment rating curves, involving the analysis of water quality parameters at different stream discharges. These empirical relationships may then be used to predict sediment output from the streamflow record. Sediment rating curves have long been used as a research tool in fluvial geomorphology (Campbell and Bauder, 1940), and using the technique various workers have measured denudation rates within a

diverse range of environments (Walling, 1971; Imeson and Ward, 1972; Lewin et al, 1974; Loughran, 1977).

A number of criticisms have been levelled against the technique. Loughran (1977) describes differences of 8% in estimates of sediment depletion produced by different regression procedures, thus a wide margin of error in estimate is possible (Finlayson, 1978; Walling, 1978). To improve accuracy of prediction, a large number of water samples were analysed through various hydrological conditions and over an extended data collection period. Walling (1977, 1978) suggests that more accurate assessments of sediment loss may be made using hourly values of stream discharge, as opposed to daily values. Hence, prediction here is based upon hourly digitised values of stream discharge, to produce a more rigorous estimate of sediment output.

Sediment rating procedures enable quantitative estimates of fluvial denudation to be made, and although subject to some error, they allow comparative analyses with denudation rates in a variety of environmental milieux, where the estimate is based upon the same procedures. Such comparisons should establish the intensity and magnitude of fluvial erosional processes within the heather moorland environment.

THE PEBBLE STUDY

Most catchment studies concentrate on sediment loss from the catchment outlet. However, recently workers have stressed the need to investigate processes within the catchment (Imeson, 1977). Thus, the magnitude of intra-basin sediment movement was assessed by a pebble study, as described in Chapter 2.

The results of this field experiment suggest a low order of magnitude of intra-catchment sediment movement. The movement of marked pebbles between April 1978 and April 1979 was measured, and of the 100 pebbles deposited within the catchment, 85 were recovered. Generalisations on the relationships between pebble size, weight and movement are difficult. The weight of recovered pebbles in Rill B was significantly different from those in Rill C, as revealed by the T-statistic ($T = 4.97$, $N = 15$, $P = < 0.001$). The difference may be explained by the loss of smaller pebbles within Rill C. Furthermore, the distances moved were very different. Rill B was within a relatively open canopy hence more pebble movement occurred than in Rill D which traversed a dense heather stand. Consequently mean distance moved was significantly different (Table 13).

Since the pebbles were all within a heather environment the entire data set may be considered as one population. One may observe inter-relationships between pebble variables (Table 14). A positive correlation exists between pebble weight and distance moved, significant at the 0.01 confidence level (Fig. 15).

Due to the difficulty in measuring pebble movement within dense heather stands some inaccuracy in measurement did occur. Thus, some results indicate slight upslope movement (the negative values). However, these pebbles were probably stationary during the experimental period.

Greater pebble movement with weight may be due to several processes. The larger pebbles may block the flow of water within the Rills, thereby encouraging traction, while smaller ones become buried in silt and possess greater friction in relation to surface area

TABLE 13

T-test of distance of
Pebble Movement in the 4 Rills

RILL	MEAN DISTANCE	T VALUE	D.F.	PROBABILITY
A B	7.1 16.0	-1.44	19	0.166
A C	7.1 26.8	-2.65	15	0.018
A D	7.1 4.0	0.77	19	0.45
B C	10.19 26.8	-1.97	15	0.068
B D	20.3 3.3	2.96	23	0.007
C D	26.8 3.3	2.41	15	0.029

TABLE 14

Correlation Matrix of Pebble Variables

N = 85

————— Significant at 0.05 level

===== Significant at 0.01 level

Long Axis	<u>0.88</u>			
Short Axis	<u>0.86</u>	<u>0.77</u>		
Index of Roundness	-0.09	<u>0.19</u>	<u>-0.43</u>	
Distance Moved	<u>0.36</u>	<u>0.23</u>	<u>0.22</u>	-0.05
	WEIGHT	LONG AXIS	SHORT AXIS	INDEX OF ROUNDNESS

(Kirkby and Kirkby, 1974).

Multiple regression of the data only yielded 19.8% explanation of variance. The equation has the form :-

7(1)

$$D = 2.16 (W) - 10.72 (L) - 14.01 (S) + 42.04$$

Multiple $r = 0.45$

$N = 85$

where $D =$ Distance moved (cm)

$W =$ Weight (g)

$L =$ Long axis (cm)

$S =$ Short axis (cm)

Although explanation of pebble movement is low, one can observe that the actual magnitude of pebble movement is low. Distance of pebble movement varies between 0 and 106 cm. These pebbles were placed in the Rills which, in Chapter 6, were identified as the hydrologically most active portions of the catchment. Despite intermittent discharge mean distance moved is only 13.4 cm, with a mean weight of 10.1 g.

There are few experiments for comparison. Most studies using the pebble technique on slopes are within alpine and tundra environments (Rudberg, 1967). Marked pebbles on unvegetated talus slopes in Alberta, Canada, moved up to 3.5 m per year (Gardner, 1979) while in the Snowy Mountains, Australia, mean annual movement of large stones (diameter in excess of 10 cm) ranged between 7.6 and 36.3 cm (Jennings and Costa, 1978). Movement of marked stones is even more rapid on semi-arid slopes (Moeyersons and De Ploey, 1976) with marked pebbles moving up to 50 cm during one storm in

Arizona (Kirkby and Kirkby, 1974).

The relatively low order of pebble movement within Wintergill suggests that heather impedes sediment movement. The degree to which movement is impeded is undergoing further evaluation, by comparison with post-burn pebble movement (C. Dunn, pers. comm.).

THE PROPERTIES OF FLUVIAL SEDIMENT DISCHARGE

Sampling of suspended sediments was conducted over an 18 month period (April 1978 to November 1979). The extended sampling scheme allowed the collection of stream water samples through a variety of hydrological conditions and seasons.

The subsequent discussion focusses upon the properties of suspended sediments and their relationships with other environmental variables. Initially, the characteristics of particulate sediment discharge are examined, in particular its relationship to stream discharge. Some of the properties of suspended solids are discussed, including the organic fraction and the size characteristics. The discussion on particulate sediment discharge is concluded with an examination of bedload loss from the catchment, following a similar analysis of solutional constituents an assessment of the total sediment load is attempted.

i) Particulate sediment load and stream discharge

In Chapter 6, the fluvial response to precipitation input was noted. Stream discharge itself, however, invokes a response in the sediment load. Suspended sediment concentrations tend to increase with stream discharge as higher water velocities increase the competence for entrainment and transport and wash load enters the channel from adjacent slope runoff.

The data provides evidence of a positive relationship between stream discharge and suspended sediment discharge. Correlation is maximised when the relationship is double logarithmic ($r = 0.48$, $P < 0.001$, $N = 202$). The relationship may be given the form :-

7(2)

$$C = 4.467 \cdot Q^{0.374}$$

where C = Suspended sediment concentration (Log_{10}) (Mg l^{-1})
= Stream discharge (Log_{10}) (l sec^{-1})

Plotting the data produces considerable scatter around the regression line (Fig. 16), a feature similarly reported by Walling and Teed (1971) in Devon ($r = 0.39$) and for two catchments in Somerset ($r = 0.11$ and $r = 0.58$) (Finlayson, 1977). The variance in suspended sediment concentration explained by stream discharge is only 22.9%, therefore other variables must be important. Two particular complicating factors are given further attention, the position of the sediment sample on the flood hydrograph and the effect of season on sediment availability.

ii) The Hysteresis effect

Several workers emphasize the importance of the hysteresis effect in complicating the relationship between fluvial and sediment discharge (Goto, 1961; Arnborg et al, 1967; Walling and Teed, 1971; Burgess, 1976; Finlayson, 1977; Loughran, 1977; Crisp and Robson, 1979). Sediment concentrations are generally greater on the rising limb of the storm hydrograph than the falling limb and the effect is explained by Arnborg et al (1967) who state

"... the first sediment entrained, during rising stage, was that last deposited by the preceding falling stage. It lies loosely on the channel bed and is readily eroded."

Thus, the initial rise in discharge flushes out loose material, with the result that maximum sediment concentration usually precedes peak discharge.

An example of the flood of May 5/6, 1978 demonstrates the effect (Fig. 17a). Peak sediment production preceded maximum discharge by 2 hours, after which concentrations declined rapidly. On the recession limb although discharge remained high sediment concentrations approximated only $1-3 \text{ mg l}^{-1}$, thereby forming a clockwise sediment rating loop (Fig. 17b).

To test these differences, the data were divided into rising and falling/steady stage recordings. Fluvial and suspended discharge during the two phases is significantly different (Table 15).

Thus, rising stage conditions tend to transport more fluvial and suspended sediment discharge than the equivalent falling stage.

Regression analyses tested the relationship between sediment and fluvial discharge on the two stages. The correlation between sediment concentration (mg l^{-1}) and stream discharge (l sec^{-1}) for the rising limb is maximised when the relationship is linear ($r = 0.44$, $P = < 0.001$, $N = 56$). Regression of the relationship yields 18.9% of explanation of variance. The equation has the form :-

7(3)

$$C = 3.399 (Q) + 7.603$$

On the receding/steady stage correlation between fluvial and sediment discharge is maximised when the relationship is double logarithmic. The correlation coefficient between discharge (Log_{10}) and sediment concentration (Log_{10}) is $r = 0.51$ ($P = < 0.001$,

N = 146). Regression of the relationship allowed 26.4% of explanation of sediment concentration variance. The relationship is given by the equation :-

7(4)

$$C = 3.66 \cdot Q^{0.373}$$

A stream discharge of 1 sec^{-1} would yield a predicted sediment concentration of 11.00 and 3.67 mg l^{-1} for the rising and falling/steady stages, respectively. Hence, sediment concentration is some 3.0 times greater on the rising limb than the recession limb of the hydrograph.

Catchment characteristics will also influence sediment yields. The availability of particles for transportation will be partly dependent on antecedent flood conditions. If the time elapsed since the previous flood event is insufficient for the release of weathered material from the catchment, then the sediment available for translocation by the rising limb will be low. For example, two rises in stream discharge during March, 1979, produced only a small increment in sediment concentration. These rises followed Spring floods, hence sediment availability was low. A rise in discharge from 2.2 to 3.3 l sec^{-1} produced a peak sediment concentration of 8.9 mg l^{-1} . Similarly, a rise in discharge from 5.9 to 7.0 l sec^{-1} produced a peak sediment concentration of 3.0 mg l^{-1} . In contrast, relatively small runoff events after the Summer dry period, produced relatively high sediment concentrations. Thus rises in stream discharge from 0 to 0.4 and 0 to 0.6 l sec^{-1} recorded peak sediment concentrations of 16.5 and 55.2 mg l^{-1} , respectively.

TABLE 15

T-test of suspended sediment and
fluvial discharge on different hydrograph limbs

VARIABLE	MEAN RISING LIMB	MEAN FALLING LIMB	T-VALUE	D.F.	SIGN.
Discharge (L sec ⁻¹)	9.80	2.069	6.37	200	<0.001
Suspended sediment concentration (Mg l ⁻¹)	2.84	0.802	5.54	200	<0.001

TABLE 16

T-test of suspended and
fluvial discharge during Summer and Winter

VARIABLE	MEAN SUMMER	MEAN WINTER	T-VALUE	D.F.	SIGN.
Discharge (L sec ⁻¹)	4.624	1.2751	5.40	200	<0.001
Suspended sediment concentration (Mg l ⁻¹)	16.489	6.9973	7.73	199	0.020

Hysteresis and sediment depletion effects result in a large degree of independence of sediment concentration from stream discharge. This is demonstrated using the equation given by Walling (1974), which has the form :-

7(5)

$$\text{Log } C = K + \text{Log } X_1 - X_2 - \text{Log } X_3 + \text{Log } X_4$$

where X_1 = Stormflow discharge at time of sampling, as defined as level of flow above that preceding hydrograph rise (1 sec^{-1})
 X_2 = Time relation to peak (+/- mins)
 X_3 = Flow level preceding storm hydrograph
 X_4 = Index of Flood Intensity

given by :-

7(6)

$$\frac{\text{Hydrograph peak} - X_3}{\text{Time of rise}} \quad (1 \text{ sec}^{-1} \text{ hr}^{-1})$$

As X_1 and X_3 contained a number of zero observations, they were not log-transformed. The equation was applied to 87 storm flow sediment samples, and may be given the form :-

7(7)

$$\text{Log } C = 1.319 - 0.00004 (X_1) + 0.00043 (X_2) - 0.213 (X_3) - 0.045 (X_4).$$

$$\text{Multiple } r = 0.68. \quad N = 87.$$

This equation improves the explanation of variance, above the simple rating equation, to 46.58%. However, sediment concentration is not significantly correlated with either X_1 or X_4 , but there is a significant correlation with X_2 ($r = 0.53$, $P < 0.001$, $N = 87$) and with X_3 ($r = -0.40$, $P < 0.001$, $N = 87$). The positive

association between $\log C$ and X_2 refers to the hysteresis effect, while the negative association between $\log C$ and X_3 is probably due to sediment depletion effects, with sediment loss decreasing with higher antecedent discharge levels.

These processes may be introduced to explain the scatter of sediment concentration on the rising limb (Fig. 16). On the scattergram, moderately high rising-limb discharges are often associated with relatively low sediment concentrations. Consequently, rising and recession limb values are not separately distributed in some parts of the scattergram.

iii) Season and sediment discharge

Several workers have discussed seasonal trends in denudation rates (Wischmeier, 1962; Hall, 1967; Wilson, 1972; Loughran, 1977). Particular emphasis has been placed on the effect of high intensity Summer storms in producing relatively large suspended sediment discharges. To test such a hypothesis the data were divided into 'Summer' (May to October) and 'Winter' (November to April) components. Analysis of variance revealed significantly higher mean suspended sediment and fluvial discharge rates in Summer (Table 16). Analyses of relationships reveal seasonal differences in the rating equations. During 'Summer' the correlation between stream discharge ($l \text{ sec}^{-1}$) and sediment concentration (mg l^{-1}) was maximised when the relationship was linear ($r = 0.44$, $P = 0.033$, $N = 60$), although the amount of variance accounted for is only 19%. The equation takes the form :-

7(8)

$$C = 3.236 (Q) + 1.508$$

Correlation between the two variables during 'Winter' is maximised when the variables are both logarithmic ($r = 0.48$, $P = < 0.001$, $N = 141$), increasing the explained variance to 23.0%. The regression equation may be given as :-

7(9)

$$C = 4.167 \cdot Q^{0.414}$$

Using these equations predicted sediment concentration for discharges of 1, 5 and 10 l sec⁻¹ would be 4.7, 17.7 and 33.9 mg l⁻¹ in Summer, and 4.2, 8.1 and 10.8 mg l⁻¹ in Winter respectively. These results suggest that sediment concentrations per unit volume of discharge are greater in Summer than Winter, and two processes may explain the difference. Firstly, as suggested by Wischmeier (1962) and Hall (1967) Summer rainfall tends to be more intense. Table 11 demonstrates that mean maximum precipitation intensity is 11.1% greater in Summer than Winter. Furthermore, sediment depletion effects will be greater in Winter, as suggested by the negative association between Log C and X₃ in equation 7(7).

iv) Organic suspended sediments

Particulate sediments consist of both mineral clastic material removed from the catchment and organic matter, but these sources must not be regarded as physically distinct. In Chapter 8 the chemical symbiosis between mineral and organic substances within the soil, in particular the clay-organic complex, will be given further consideration. Evidence suggests that organic matter forms a significant portion of particulate sediment discharge from the moorland environment (Arnett, 1977; Finlayson, 1978) the sources of which are both autochthonous and allochthonous (Jackson, 1975). The sediments themselves contain a variety of

organic materials. Particulate organic matter identified within a Perthshire stream draining a heather moor catchment included invertebrate fauna, unicellular and filamentous algae, phytoplankton and a non-living fraction consisting of invertebrate exuviae and fragments of dead plant and animal matter, in various forms and various stages of decomposition (Egglshaw and Shackley, 1977).

Organic matter forms a significant portion of total suspended solids. Comparison of total particulate concentration with organic sediment concentration requires some caution as measurement errors are particularly important when concentrations are low. Thus, particulate organic matter varied from an over-estimate of 108% to 2.37% of total suspended solids weight, with a mean of 35.9%. Such a figure agrees broadly with the 20 to 40% range observed within North York Moors streams by Arnett (1978).

The correlation between particulate organic concentration and discharge is not significant ($r = 0.03$, $P = 0.41$, $N = 73$), although an association was observed between stream discharge ($l \text{ sec}^{-1}$) (Log_{10}) on the rising limb and particulate organic concentration (mg l^{-1}) ($r = -0.45$, $P = 0.010$, $N = 26$). Regression of the relationship yields 20.4% of explanation of organic sediment variance. No significant correlation coefficient was found between the two variables on the receding/steady stage ($r = 0.12$, $P = 0.218$, $N = 47$).

Rising stage discharge may cause a decrease in both autochthonous and allochthonous organic sediment concentrations as the former will be flushed downstream, thus causing a decrease in particulate suspended organic sediment concentration (Hynes, 1970; Crisp and Robson, 1979).

Fisher et al (1979) suggest that the transport of organic materials can be related to hydraulic parameters describing fluid motion. Thus, the allochthonous sediments may respond to rising stage discharges as the competence of the stream to transport mineral sediments is increased. The low specific gravity of allochthonous organic sediments allows their translocation and transportation by relatively low stream discharges.

The specific gravity of soil samples from the upper 10 cm of Wintergill catchment were measured, separate analyses of two samples being made of the surface litter fraction, air-dried fine-earth fraction and mineral fractions. Organic matter was removed from the latter sample by loss-on-ignition (850°C for ½ hour). The results reveal considerable differences in the specific gravities of these surface materials. Mean litter specific gravity was 1.05, compared with a mean figure of 1.28 for the fine-earth fraction and 2.50 for mineral soil. Thus Calluna litter would be more readily translocated by surface water than soil, with mineral soil being most stable. Consequently, low discharges are more competent to transport organic materials, whereas higher discharges may transport denser mineral sediments.

v) Suspended sediment size

Coulter Counter results (Table 17) indicate that suspended particles are predominantly in the fine and medium silt ranges (Avery, 1973). The mean size-distribution of the samples demonstrates that most particles are recorded in the 6 to 9 µm diameter range. Relatively few particles were recorded in the coarse-silt range (> 20 µm). Particles coarser than 43 µm were detected in only two samples with none exceeding 54 µm.

The results agree with Colby (1963), indicating that wash load is predominantly composed of silt-sized material. This is further confirmed by Rendon-Herrero (1974) reporting a suspended sediment size-distribution ranging between 1 to 100 μm , with over 50% by weight of the particles in the finer than 30 μm size-range, within the Bixler Run watershed, Pennsylvania. Both the Bixler Run and Wintergill sediments are relatively fine when compared with results from turbid rivers of New South Wales, where suspended particles in excess of 500 μm were detected using similar techniques (Walker et al, 1974). In comparison, Carson et al (1973) report suspended sediment sizes in excess of 300 μm during Spring runoff in the Eton River, Quebec. Thus, the suspended sediments of Wintergill catchment are relatively fine.

Correlations were observed with other suspended sediment properties. The total number of particles in the silt-range (t.s.) correlates significantly with total organic load (mg l^{-1}) ($r = 0.41$, $P = 0.013$, $N = 69$). Furthermore, the total number of particles in the 21 to 34 μm size range correlates with dissolved organic load (mg l^{-1}) ($r = 0.21$, $P = 0.041$, $N = 69$).

Computation of sediment weight provided evidence of the predominance of fine and medium silts in suspended solids discharge. For each class range, the geometric mean particle diameter was calculated from the formula :-

7(10)

$$N \sqrt{XY}$$

where

X = Lowest particle diameter of distribution

Y = Upper particle diameter of distribution

N = Number of intervals.

For each class range, a geometric mean particle diameter was assumed to represent that range. The volume of particles, in a given class range, was calculated using the equation :-

$$7(11) \quad 1 \text{ T.U.} = \left(\frac{4/3 \left(\frac{D}{2} \right)^3}{\text{Median T.U.}} \right)$$

where 1 T.U. = 1 Threshold unit.

D = Diameter of calibration particles (Paper mulberry pollen 13.31 μm).

Median T.U. = Median threshold unit achieved using calibration procedure (Coulter Electronics Limited, Technical Manual, 1968).

The volume (μm^3) represented by the mean number of counts, for each geometric mean size, was calculated. As conversion of volume to weight requires an estimate of specific gravity, the analytically determined figure of 1.28 was considered to be representative. Consequently, the weight and percentage total weight of each geometric mean particle size could be calculated (Table 18).

Suspended solids appear to be transported mainly in sizes less than that investigated using the Coulter Counter. Extrapolation of sediment weight would yield a mean sediment concentration of 0.52 mg l^{-1} . Mean particulate sediment concentration for the samples is 9.92 mg l^{-1} . Even allowing a margin of error, a considerable portion of sediment appears to be transported in size-ranges not measured by the Coulter Counter. As the sediment size-distribution was open-ended above a particle diameter of $6 \mu\text{m}$, one might infer that the greatest weight of suspended sediments have particle diameters less than $6 \mu\text{m}$.

TABLE 17

Summary of Coulter Counter Results

Aperture size (μm)	Maximum number of particles greater than aperture size	Minimum number of particles greater than aperture size	Mean number	Number of samples
6	3487.0	0.0	366.93	85
9	1725.0	0.0	98.61	74
14	181.0	0.0	18.49	74
21	19.0	0.0	2.57	74
34	4.0	0.0	0.20	74
43	2.0	0.0	0.041	74
54	0.0	0.0	0.0	74

TABLE 18

Mean volume and weight characteristics
of particulate suspended solids

Aperture size (μ)	Geometric mean size (μ)	Volume equivalent of 1 count	Mean no. of counts	Volume (μ^3)	Mg l ⁻¹	% total weight
6 - 9	7.10	201.87	366.93	54165.75	0.13866	26.77
9 - 14	11.21	829.92	98.61	66493.19	0.17022	32.86
14 - 21	17.05	2962.23	18.49	47158.70	0.12072	23.30
21 - 34	26.96	11311.45	2.57	26808.14	0.06863	13.25
34 - 43	38.01	32023.09	0.20	5091.67	0.01303	2.52
43 - 54	47.78	64253.94	0.041	2634.41	0.00674	1.30
54 - 67	60.06	130911.83	0	0	0.0	0.0

Examination of the size-distribution of measured samples reveals the dominance of medium-silts (Fig. 18). Particles finer than 20 μm accounts for a mean 53.3% of the weight of the suspended solids with only 5.9% by weight exceeding 40 μm .

These results suggest that Wintergill transports suspended solids mainly in the fine to medium-silt-size ranges, the predominance of fine-silts being inferred from the difference between predicted and measured parameters. Measured samples fall mainly into the medium-silt range by weight and volume, and the significance of such a finding is given further consideration when the textural properties of bedload sediments have been examined.

BEDLOAD SEDIMENTS

Over the annual cycle (April 1 to March 26 1979) 68.2 Kg of bedload material were collected by the trough (Fig. 19) mainly associated with the rising limb of the flood hydrograph. For example, prior to the storm event of May 5-6 1978 the bedload trap was empty. Over a nine-hour period, discharge increased from 0.5 to 15.3 l sec^{-1} . The estimated flood volume of 202.54 m^3 of water accounted for 15.8% of monthly discharge in only 1.1% of the time, and transported almost all of the 11.2 Kg of bedload trapped during May. Thus, actual bedload transportation is associated with short duration flood events.

Bedload transportation is uneven throughout the year being high in Winter and relatively low in Summer. During the 162 day period June 1 to November 4 1978 (44% of the year) 7.3 Kg of bedload was collected representing only 10.7% of annual production. Most of the bedload transported during this period was transported by one Summer storm on July 30.

TABLE 19
Textural analysis of bedload sediments

Major Textural Group	Minor Textural Group	Size Range (mm)	% total weight (> 1 Kg samples)	% total weight (< 1 Kg samples)
COBBLES	COBBLES	> 600	2.19	0
GRAVEL	COARSE GRAVEL	200 - 600	28.60	13.92
	MEDIUM GRAVEL	200 - 6.0	23.06	25.79
	FINE GRAVEL	2.0 - 6.0	21.52	16.66
SAND	COARSE SAND	2.0 - 0.6	15.26	18.00
	MEDIUM SAND	0.6 - 0.212	6.42	12.22
	FINE SAND	0.212 - 0.063	2.95	10.89
SILT/CLAY		< 0.063	0.80	2.52
	COARSE SILT	0.063 - 0.020	0.75	1.97
	MEDIUM SILT	0.02 - 0.006	0.002	0.55
CLAY	FINE SILT	0.006 - 0.002	0.00	0.00
	CLAY	0.002	0.008	0.00

Snowmelt during Winter and early Spring was responsible for a large portion of bedload transport. During the 63 day period between January 15 and March 26 1979 some 31.4 Kg of bedload was trapped and this may be an underestimate as floods often filled the trap completely. Nevertheless, according to the data in 17.5% of the year, 40.1% of annual bedload was transported.

Bedload transportation was particularly high in early Spring, when, between March 6 and March 26, 16.4 Kg of bedload were collected. Thus, in only 3.6% of the year, 24% of bedload was removed, this period coinciding with the Spring snowmelt. Minimal loss occurred subsequently with only 2.2 Kg of bedload being collected between March 26 and July 5, 1979.

Textural analysis of the bedload sediments revealed their generally coarse nature. When more than 1 Kg of bedload was available for any particular month random 1 Kg samples were taken. The remaining 4 samples were mixed and analysed as a whole.

The large bedload sample demonstrated that gravels formed the largest textural component (Table 19). Cobbles only constituted 2.2% of total weight in the 8 Kg sample. However, gravels accounted for 73.2% of weight, while sand accounted for 24.6% of weight. Only some 0.8% by weight of the sample was finer than sand.

The smaller bedload sample is texturally somewhat finer (Table 19) with no cobbles, 56.4% gravel and 41.1% sand. The finer-than-sand fraction was proportionally greater than in the large sample, accounting for 2.5% of total weight.

Pipette analysis examined the size characteristics of the fraction

finer than 63 μm , revealing that most of the silt-clay material is in the coarse-silt range. In the large sample, material finer than coarse-silt constitutes a very small part of the bedload sediments while, in the small sample, medium-silt forms a significant portion. However, in both samples fine-silt and clay formed very small portions of the sediments.

Reviewing the bedload and Coulter Counter data, some comments may be made regarding the nature of sediment transport from Wintergill. Coulter Counter analysis failed to reveal particles coarser than 54 μm . Thus, suspended sediment discharge appears to be restricted to the transportation of silts. Material coarser than medium-silt appears to be transported as bedload. The largest component of bedload sediments being gravels. Thus, evidence supports the hypothesis of Colby (1963) and Rendon-Herrero (1974) that wash load is of material in the silt range, while bedload is coarser material. However, during flood events, coarse saltating particles could be regarded as temporary wash load, thus the two forms of sediment load are not necessarily distinct but the degree of distinctiveness may depend on stream discharge.

DISSOLVED SEDIMENTS

Dissolved sediment forms a relatively large and consistent portion of the total suspended load. Mean particulate suspended sediment concentration is 9.8 mg l^{-1} , compared with a mean solute concentration of 89.5 mg l^{-1} (N = 85). Whereas particulate suspended sediment concentrations varied between 0 and 140 mg l^{-1} , solute concentration varied between 36.0 and 156.6 mg l^{-1} . Stream discharge appears to affect solute levels, a significant correlation being calculated between the two variables ($r = -0.21$, $P = 0.027$, $N = 85$). The equation may be given as :-

7(12)

$$S = 88.52 \cdot Q^{-0.0359}$$

where S = Suspended dissolved sediment concentration (mg l^{-1})

The negative association may be explained by the dilution effect. During baseflow conditions, moisture within the soil matrix approaches ionic equilibrium (Oxley, 1974). The amount of solute uptake by soil moisture will depend on residence times, as has been demonstrated by field investigations in Scotland and laboratory simulations (Trudgill et al, 1980) and in a small forested Luxembourg catchment (Verstraten, 1977). The type of ions is also an important factor, as uptake of silica and several cations may occur within several hours (Smith and Dunne, 1977). Storm events allow the rapid throughput of water which has not undergone ionic exchange to the same extent. The solute concentration of stormflow is considerably less than for soil moisture in a small Somerset catchment described by Burt (1979). Stormflow generally dilutes ionic-rich water inducing lower concentrations in the stream system. Several workers have reported the dilution effect within a diverse range of fluvial environments (Hall, 1967; Lewin et al, 1974; Oxley, 1974; Arnett, 1977; Finlayson, 1978; Foster, 1978; Burt, 1979). Regression of the solute concentration-discharge relationship often produces considerable scatter about the line of best fit (Lewin et al, 1974). For the Wintergill data discharge only explains 4.4% of solute variance. Indeed, Finlayson (1977) found no significant correlation between dissolved solids concentration and discharge within the lower basin of East Twin Brook, Somerset. Obviously other factors influence the discharge-solute relationship. In an investigation of solute loss from a Devon catchment Foster

(1978) recognizes 13 variables which influence solute loss.

The flushing effect has regularly been cited as a complicating variable. Early storm-water flushes out the ionic-rich soil moisture retained within the soil matrix (Oxley, 1974). From observations on a woodland catchment in Maryland, U.S.A., Cleves (1970) suggests that the flushing effect is essentially a process whereby salts within organic debris are flushed out and cations from clay minerals are replaced by H⁺ ions in rainfall. Nakamura (1971) and Edwards (1973b) report a similar effect in instrumented catchments in Japan and England, respectively.

To investigate the flushing effect within Wintergill catchment, the data were divided into readings for rising and falling/steady stages. Analysis of variance, however, failed to reveal any significant difference between solute concentrations on the rising or falling stages (Table 20).

An examination of the relationships between solute levels and stream discharge suggests that a dilution effect is operative only on the rising limb of the hydrograph. The correlation coefficient between solute load and discharge on the rising limb is $r = -0.33$ ($P = 0.033$, $N = 32$). Thus, the strength of the relationship is much greater on the rising limb than it is overall. No association occurs between the two variables for the recession/steady stage data ($r = 0.0052$, $P = 0.486$, $N = 47$).

Regression of the solute-discharge relationship on the rising stage increases explanation of variance above the overall level to 11.1%.

The relationship may be given as :-

7(13)

$$S = 89.54 \cdot Q^{-0.0928}$$

These relationships do not generally concur with reported data.

The simple dichotomy between flushing on the rising stage and dilution on the receding stage was not found. Rather, it would appear that dilution is only effective during rising stages while the low gradient of the regression slope suggests that solute concentrations declines very gently with increasing discharge.

The strengthened negative association suggest that dilution is operative on the rising stage. Although flushing may occur, no evidence can be found in the solute data. On the recession/steady limb, solute load does not appear to respond to changes in stream discharge. Hence, other variables must influence solute load. Explanation may lie in the "buffering" capability of peaty gley soils (Arnett, 1978, cf. Chapter 8). Pedological-edaphic variables influencing solute release from the catchment may buffer the loss of solutes against changing hydrometeorological and hydrological conditions. Thus, solute load may be independent of stream discharge.

DISSOLVED ORGANIC SEDIMENTS

A small portion of dissolved solids load is organic. Dissolved organic sediment concentrations (D.O.M.C.) vary between 0 and 12.3 mg l⁻¹, with a mean of 2.2 mg l⁻¹ (N = 79), approximately 2.4% of mean total solute concentration.

Such low values accord broadly with other reported observations. Within a woodland catchment in New Hampshire, U.S.A., dissolved organic concentrations varied between 0.4 and 2.9 mg l⁻¹ (Hobbie and Likens, 1974), confirmed more recently within the same catchment by Bilby and Likens (1979) who report concentrations between 2 and

3 mg l⁻¹. In England Osborne et al (1980) report values of between 1.0 and 2.2 mg l⁻¹ for the River Wye. Even within the contrasting environment of a thermal artesian desert stream in California D.O.M.C. varied only between 3 to 4 mg l⁻¹ (Naiman, 1976).

Higher values have been observed in a variety of environments. D.O.M.C. within the heathland catchment, of the River Win, Dorset, was 10.1 and 11.1 mg l⁻¹ for two samples (Baker et al, 1974). Comparable D.O.M. concentrations were reported by Arnett (1978), where mean concentrations for 16 North York Moors catchments varied between 8.4 and 18.9 mg l⁻¹. These values compare with those reported within estuaries (6-14 mg l⁻¹) (Naiman and Sibert, 1978) and swampland environments (Mulholland and Kuenzler, 1979).

Dissolved organic matter appears to be strongly associated with stream discharge ($r = -0.62$, $P < 0.001$, $N = 79$) the latter accounting for 38.2% of variance (Fig. 20). The equation may be given as :-

7(14)

$$\text{D.O.M.C.} = 1.505 \cdot Q^{-0.5413}$$

This dilution relationship appears to be stronger and more straightforward than the dilution effect with total dissolved sediments, and a number of processes may be postulated. The biomass probably contributes most of the dissolved organic matter, a conclusion reached after laboratory simulation of a woodland catchment (Wetzel and Manny, 1972). Within Callunetum moorland soil moisture will become enriched with humic and fulvic acids secreted from heather litter (Grubb and Suter, 1971). As baseflow is dominated by the release of this soil moisture into the stream,

the allochthonous dissolved organic concentrations will be relatively high. Storm events, involving the movement of "non-organic" water through the catchment system, will tend to dilute the organically-enriched soil moisture.

Autochthonous organic sediments may also be present although the ephemeral nature of stream discharge is generally inimical to the development of aquatic fauna (N. Jones, pers. comm.)

Nevertheless, certain organisms, particularly algae, may secrete dissolved organic acids (Lampert, 1978) and this autochthonous fraction will also be diluted by the entry of stormflow into the stream, ~~further contributing to the dilution effect.~~

Evidence for these processes is sparse, reflecting the lack of research into this particular aspect of fluvial processes. Some workers suggest a positive relationship between D.O.M.C. and stream discharge, while others report either a negative or nil relationship between the two variables. Within a forested sub-catchment of Hubbard Brook, New Hampshire, Fisher (1970) reports a positive correlation between D.O.M.C. and stream discharge. The positive relationship was attributed to biotic factors, in particular the flushing of dissolved organic matter from leaf fall. Other researchers report no detectable relationship between stream discharge and dissolved organic concentrations. Within the main Hubbard Brook catchment the relationship was not found (Hobbie and Likens, 1973) a conclusion supported for sub-catchments within the North York Moors (Arnett, 1978).

A plausible explanation for the lack of relationship between D.O.M.C. and stream discharge is that catchment soils may act as a "buffering" system, moderating the release of dissolved organic

matter from the soil. Thus, the soils will allow the release of D.O.M., but not in direct response to prevailing hydrometeorological conditions.

Little evidence has been presented for a negative relationship between D.O.M.C. and fluvial discharge. Brinson (1976) reports a tendency for D.O.M.C. to decrease during floods, within four Guatamalan catchments, although insufficient data were available for statistical analysis.

The possibility of a flushing effect upon the dissolved organic sediments was investigated by dividing the data set into rising and falling/steady stage recordings. Analysis of variance indicates that D.O.M.C. are significantly different on the two hydrograph limbs (Table 20), while analysis of the correlation results suggest that dilution is a more effective process on the receding limb of the hydrograph.

Regression analysis reveals that discharge is a more important variable in explaining variations in D.O.M.C. on the recession limb of the hydrograph, than on the rising limb. These relationships may be given as :-

7(15) RISING LIMB
D.O.M.C. = 1.219. $Q^{-0.3826}$
($r = -0.33$, $P = 0.033$, $N = 32$).

7(16) FALLING LIMB
D.O.M.C. = 1.588. $Q^{-0.5641}$
($r = -0.69$, $P = <0.001$, $N = 39$)

Several interesting points emerge from this analysis. Firstly, the

TABLE 20

T-test of dissolved suspended solids

Variable	Mean rising limb	Mean falling limb	T-value	D.F.	Sign.
Discharge ($l \text{ sec}^{-1}$)	3.7029	1.7431	3.43	71	<0.001
Solute load ($mg \text{ l}^{-1}$)	85.59	92.66	-1.74	63	0.087
Dissolved organic load ($mg \text{ l}^{-1}$)	1.29	2.82	-2.40	77	0.010

degree of association is much stronger on the recession limb where 47.0% of variance is explained compared with 10.9% for the rising limb data. The steepness of the regression slope is somewhat greater on the recession limb, indicating a greater change in D.O.M.C. with discharge (Fig. 20).

A number of hypotheses may be offered to explain these differences. Rising stages may flush out dissolved organic matter from the soil-biomass system (Cleves, 1970; Fisher, 1970), producing an effect similar to the clockwise hysteresis loop for suspended solids. Consequently, a mixture of flushing and dilution may be operative upon the dissolved organic sediments during rising stages producing an overall negative association but with a low explanation of variance.

The dilution effect appears more strongly on the recession limb, where any initial flushing operative during rising stage will have ceased and stream discharge simply dilutes the allochthonous and autochthonous dissolved organic fraction. Consequently, the negative relationship between D.O.M.C. and stream discharge is stronger and more pronounced than on the rising stage.

The discussion implies that the processes influencing the dynamics of dissolved organic sediment are complex and little understood. Within Wintergill catchment there appears to be a negative relationship between dissolved organic sediment concentration and stream discharge, with stormflow diluting allochthonous and autochthonous components, thereby encouraging a decrease in D.O.M.C. with discharge. The effect appears to be complicated by the flushing of dissolved organic sediments from the soil-vegetation system during rising stage situations.

TOWARDS A SEDIMENT BUDGET

Discussion has so far concentrated upon sediment characteristics and the relationships between stream and sediment discharge. Although runoff is one variable influencing sediment concentrations, the complicating effects of other factors preclude the establishment of precise causal relationships. For some types of sediment, expected relationships with discharge were not evident while for others the proportion of variance explained by discharge was low. Some workers now suggest that sediment losses can operate with a large amount of independence from stream discharge (Walling, 1974; Finlayson, 1978).

From the empirical relationships which have been observed an attempt was made to estimate total sediment loss. For each hour of stream stage record the sediment depletion for each of the sediment variables was computed using the regression equations (Table 21).

The data gaps in the streamflow record prevent a precise estimate of sediment loss. As discussed in Chapter 6 a total of 70 days of data were lost, thus streamflow records are complete for 80.8% of the year. Some data gaps coincide with periods of zero discharge, such as the 12 day gap during a dry Summer period. During Winter the catchment was covered with frozen snow, when an estimated 36 days yielded zero stream discharge. Consequently the real data gap is some 21 days in February-March and the streamflow record may be considered complete for 94.3% of the year. For much of the missing 21 days the catchment was still frozen and streamflow records were re-started when access was possible, during the initial snowmelt. Thus, the real loss of streamflow record may be a few days, but these were during erosive Spring runoff. Hence, the

TABLE 21

Summary of Regression Equations
between Stream and Sediment Discharge

(N.B.) In each case stream discharge ($l \text{ sec}^{-1}$) is the independent variable

Dependent variable	Regression Equation	Explanation of variance (%)
Suspended sediment concentration (mg l^{-1})	$C = 4.4666 \cdot Q^{0.3741}$	22.9
Suspended dissolved sediment concentration (mg l^{-1})	$S = 88.522 \cdot Q^{-0.03586}$	4.43
Suspended dissolved organic sediment concentration (mg l^{-1})	$\text{D.O.M.} = 1.50494 \cdot Q^{-0.54137}$	38.2

sediment depletion estimates discussed below are an underestimate.

1) Particulate sediment denudation

The results indicate that denudation within Wintergill by the removal of particulate suspended matter is low, at 70.74 Kg yr^{-1} . To compare the values with other reported data the values were converted to tonnes/ Km^2 /year. Such an extrapolation is somewhat artificial, but allows a comparison of the relative magnitudes.

Table 22 summarises sediment losses from instrumented catchments within the British Isles. The estimated denudation rate of $1.51 \text{ t/Km}^2/\text{yr}$ for Wintergill for suspended particulate sediment is relatively low when compared with other reported values. Denudation rates of $40,000 \text{ t/Km}^2/\text{yr}$ have been reported within actively eroding gullies on the Howgill Fells (Harvey, 1974), while at the other extreme rates of less than 2.0 have been measured for a number of catchments (Arnett, 1977; Finlayson, 1977), an order of magnitude similar to the Wintergill figure.

The extrapolated denudation rate for Wintergill is the third lowest reported in Table 22. The other low values often refer to catchments where a considerable amount of heather is present (Arnett, 1977), while it is noteworthy that the lowest reported value, that for East Twin Brook, Somerset is for a catchment with a complete Calluna cover (Finlayson, 1977). This would suggest that heather has a protective role, impeding the erodibility of the underlying soil.

Suspended solids discharge includes both organic and inorganic components. Since no rating equation could be developed for organic sediments, the accurate assessment of this fraction cannot

TABLE 22

Estimates of denudation from River samples in the British Isles

Location	Denudation t/Km ² /yr			Percentage - total load		
	Solute	Sediment	Total	Solute	Sediment	Source
Wintergill catchment	23.4	1.5	24.9	93.6	6.4	1978-79
Tyne, Bywell	61.9	116.0	177.9	35.0	65.0) Hall, 1967
Derwent, Eddybridge	91.4	215.0	306.4	30.0	70.0	
Clyde, Daldowie		51.2) Fleming, 1969
Avon, Fairholm		169.0				
Whitecart, Hawkshead		112.2) Imeson, 1970
Catchwater Drain, East Yorkshire	129.4	8.9	138.3	93.5	6.5	
Drewton Beck, East Yorkshire	59.0	1.2	60.2	98.0	2.0) Evans, 1971
Hodge Beck	54.0	480.0	534.0	11.0	89.0	
Peak District		34.4				
East Devon:) Walling, 1971
Catchment 1	32.9	9.4	42.3	77.0	23.0	
Catchment 2	55.2	37.0	92.2	60.0	40.0) Walling, 1971
Catchment 3	40.2	49.0	89.2	45.0	55.0	
Catchment 4	81.2	45.7	126.9	64.0	36.0) Harvey, 1974
Catchment 5	68.7	56.2	124.2	55.0	45.0	
Howgill Fells, Cumbria		40,000				Lewin <u>et al</u> , 1974
Maesnant, Plynlimon		4.6) Oxley, 1974
Ebyr North	73.9	12.1	86.0	92.9	7.1	
Ebyr South, Plynlimon	42.4	10.7	53.1	80.0	20.0) Burgess, 1976
Hodge Beck	38.1	30.4	68.5	56.0	44.0	
Upper Hodge Beck	36.8	25.1	61.9	59.0	41.0	
North York Moors:) Arnett, 1977
Catchment 1	113.3	1.7	115.0	98.52	1.48	
Catchment 2	56.8	4.5	61.3	92.66	7.34	
Catchment 3	49.7	2.7	52.4	94.57	5.43	
Catchment 4	35.1	1.9	37.0	94.87	5.13	
Catchment 5	42.3	4.2	46.5	90.97	9.03	
Catchment 6	34.6	2.1	36.7	94.3	5.7	
Catchment 7	39.7	1.0	40.7	90.2	9.8	
Catchment 8	53.1	4.0	57.1	92.9	7.0	
Catchment 9	75.4	2.5	77.9	96.8	3.2	
Catchment 10	61.1	1.7	62.8	97.3	2.7	
Catchment 11	25.8	4.2	30.0	86.0	14.0	
Catchment 12	71.0	4.5	75.5	94.0	5.9	
Catchment 13	72.0	32.0	104.0	69.2	30.8	
Catchment 14	48.7	6.9	55.6	87.6	12.4	
Catchment 15/16	69.3	2.2	71.5	96.9	3.1	
East Twin Brook, Somerset	16.5	0.3	16.8	98.4	1.5	Finlayson, 1977
River Wye	103.1	17.6	120.7	85.4	14.6	Osborne <u>et al</u> , 1980

be evaluated. Assuming the mean measured particulate organic concentration of 35.9% to be a representative proportion of the total particulate load, particulate organic loss will be 25.38 Kg. This value is equivalent to $0.54 \text{ t/Km}^2/\text{yr}$, leaving mineral losses as 45.36 Kg, or $0.97 \text{ t/Km}^2/\text{yr}$. Data for particulate organic denudation are sparse although figures ranging from 0.5 to $1.1 \text{ t/Km}^2/\text{yr}$ are reported for catchments within the North York Moors (Arnett, 1977). The Wintergill value lies towards the lower end of this range, suggesting minimal release of organic sediment.

Bedload transportation from the experimental catchment constitutes a relatively large component of particulate denudation. Measured bedload is equivalent to 49.08% of total estimated particulate sediment loss and 6.01% of total sediment loss. Lane and Borland (1951) suggest that bedload constitutes about 10% of total sediment discharge. Several workers report varying proportions of bedload to suspended sediment load. As little as 0.38% of suspended solids discharge was released as bedload in a lowland catchment (Imeson and Ward, 1972). For 5 Devon catchments, Walling (1974) found bedload to vary between 1.3 and 11% of total solids discharge. Bedload contributed 13% of total solids within the River Tyne at Bywell (Hall, 1967), while with reference to the North York Moors, the relative proportions were 8.6% for all Bransdale and 5.9 and 7.8% for Upper Hodge Beck and Blowarth Slack, respectively (Burgess, 1976). Extrapolation of the bedload total amounts to $1.45 \text{ t/Km}^2/\text{yr}$. Even though the bedload total forms a relatively large component of total sediment loss from Wintergill, it is quite low when compared with other reported values. For instance, Burgess (1976) reports a yield of $2.61 \text{ t/Km}^2/\text{yr}$ for Bransdale, which compares with $4.95 \text{ t/Km}^2/\text{yr}$ for an agricultural catchment in Devon (Walling, 1974) and

15.95 t/Km²/yr in the River Tyne. The Wintergill total compares quite closely with the 1.48 t/Km²/yr reported for the environmentally similar Upper Hodge Beck (Burgess, 1976).

The bedload proportion for Wintergill is relatively high. The configuration of the catchment, in particular the exposed cuttings and track, appears to allow a relatively greater loss of sediment by bedload.

2) Dissolved sediment denudation

The largest component of sediment discharge from the catchment is in the solutional phase. Estimated solute loss of 1101.16 Kg, contributes some 96.3% of estimated total suspended sediment discharge.

Comparison with other reported data collected within similar environments displays the dominance of dissolved solids in suspended sediment denudation (Table 22). Burgess (1976) found that solutes accounted for between 56 and 74% of total suspended load for 4 catchments within the North York Moors, although in the same area Arnett (1977) reports equivalent figures of 69 to 98% within 16 catchments.

Reported solute denudation rates within environmentally similar regions outside the North York Moors are broadly comparable. Oxley (1974) measured solutional phase at 92.9 and 80.0% of total suspended load for the upland catchments of Ebyr North and Ebyr South, respectively, while within a Callunetum catchment Finlayson (1977) found a comparable figure of 98.4%.

Collected data clearly suggest that most of the dissolved sediments are inorganic. Data collected within the heather-covered catchment

of Shelligan Burn indicates that mineral losses are dominated by calcium with magnesium, nitrates and phosphates of decreasing importance (Egglshaw and Shackley, 1977).

Dissolved organic losses are low, representing only 1.64% of total dissolved load. Dissolved organic sediment losses from 16 larger catchments in the same area ranged between 1.7 and 4.7 t/Km²/yr (Arnett, 1978), considerably greater than the 0.38 t/Km²/yr extrapolated for Wintergill, thus providing additional evidence for the relatively low dissolved organic loss from this experimental catchment.

3) Total sediment loss

Having examined the individual components of fluvial denudation, the sum total of sediment removal from Wintergill may be calculated. The total estimated sediment loss during the year was 1237.07 Kg, although this is probably an underestimate as indicated previously. Such a value represents a loss of 26.32 t/Km². Bedload losses are proportionately high, possibly due to anthropogenic interference in catchment morphology. Few denudation assessments incorporate bedload transport, thus an estimated 1170.9 Kg of suspended sediment was removed from the catchment, equivalent to 24.94 t/Km²/yr.

Denudation rates of such low order suggest that this catchment is an environmental system in a low state of erodibility. Comparison with other reported data demonstrates that the estimated total suspended sediment denudation is the second lowest on record (Table 22). Interestingly, the lowest reported value was also for a similar heather-covered catchment (Finlayson, 1978).

From a sediment budget viewpoint the denudation rates need not represent a net loss from the environmental system, as inputs do

occur, both from inside and outside the catchment. Inflows of sediment may occur due to both the external input of particulate matter and solutes and the internal generation of organic materials. Precipitation particulate matter and dry fallout may input sediment into the catchment (Edwards, 1973; Cryer, 1976; Finlayson, 1977; Oldfield et al, 1978). The collection of uncontaminated rain samples poses a problem, as discussed by Cryer (1976) and Finlayson (1977). However, inspection of rainwater samples collected over a one-month period (February-March, 1980) revealed no evidence of contamination (insects, bird droppings etc.), and were used for analysis.

Precipitation was in the form of weekly bulk samples collected within Wintergill catchment, presumably containing particulate sediments deposited by rainfall and dry fallout. Suspended sediment concentrations of the samples varied between 2.34 and 9.64 mg l^{-1} with a mean of 5.6 mg l^{-1} and a volume weighted mean of 5.3 mg l^{-1} . For comparison, suspended sediment concentrations in a bulk precipitation sample, collected on Sneaton High Moor, was 10.05 mg l^{-1} . The Wintergill value may be compared with a mean precipitation particulate input to East Twin Brook, Somerset, of 5 mg l^{-1} (Finlayson, 1977).

Assuming 5 mg l^{-1} to be representative then for the estimated annual precipitation of 967.4 mm , over the 4.7 ha catchment, predicted sediment input would amount to 227.34 Kg , some 3.2 times greater than estimated particulate suspended sediment output. Although such extrapolation cannot pertain to any accuracy, the evidence does suggest that particulate sediment input will tend to diminish net sediment loss, perhaps even contribute to a net accumulation.

Similar procedures may be adopted for solute inputs via precipitation. Ionic concentrations for the same samples varied between 47.9 and 102.4 mg l⁻¹, with a mean figure of 70.2 and a volume weighted mean of 67.1 mg l⁻¹. The corresponding value on Sneaton High Moor was 66.48 mg l⁻¹.

The mean East Twin Brook value of 15 mg l⁻¹ is considerably lower, although there is abundant evidence to indicate that solute levels in precipitation may vary spatially (Matveyev and Bashmakova, 1967) and temporally (Gore, 1968; Cryer, 1976). One may postulate that the higher Wintergill value is due to industrial sources of solutes (Oldfield et al, 1978).

Extrapolating the volume weighted mean solute concentration over the catchment yields an input of 3,043.01 Kg and although similar cautions apply in interpreting the results, such a solute input would exceed the estimated total solute loss by a factor of 2.82. The result may be compared with those reported by Fisher et al (1968) where atmospheric input of certain cations exceeded their output in streamwater.

Release of litter by heather will provide an input to the catchment surface for possible removal. Imeson (1971) reports a mean net surface accretion under Callunetum of 0.025 cm year⁻¹. This process was a topic of investigation within the present study, the results of which are more fully discussed in Chapter 8. In the investigation mean annual surface accretion under a Callunetum stand was 0.021 cm (N = 14). Such accumulation would, according to the collected data, amount to an accretion of surface litter of 24.74 Kg ha⁻¹, or 103.66 Kg for the mature heather covered area of the catchment.

Estimated annual particulate organic loss from Wintergill amounted to 25.4 Kg but presumably not all of this material was allochthonous, an unspecified amount representing the autochthonous component. Hence, the allochthonous portion is probably less than 25 Kg. However, as the estimated litter productivity exceeds estimated particulate organic losses by a factor of 4.08, there is further evidence to indicate a net accumulation of organic material.

This discussion must be viewed with caution as reported values incorporate data based on a limited number of samples and considerable extrapolation. Nevertheless sufficient evidence is available to draw certain conclusions. Results from sediment studies in Wintergill indicate that the catchment denudation rate is amongst the lowest reported in Britain, and may be even lower than indicated when one considers potential inputs of sediment from precipitation, the internal generation of organic materials and the autochthonous organic component. Erosional activity appears minimal and evidence suggests that mature heather moorland may not be experiencing an erosive geomorphological regime at all, but may indeed be undergoing a net accumulation of material.

While over the annual cycle sediment loads are relatively low, rates of sediment output vary throughout the cycle. Losses mainly occur during Winter. This is also reported for a lowland catchment (Imeson and Ward, 1972) and a catchment in the Rocky Mountains, U.S.A. (McPherson, 1971). Loss is particularly evident with regard to bedload transport, with nearly 75% of the annual output being evacuated in the six "Winter" months, November to April. The corresponding values for suspended sediment, dissolved sediment and dissolved organic sediment losses are 68, 65 and 58%, respectively.

CONCLUSION

From this study of Wintergill catchment, a number of processes operative within mature heather moorland may be recognized.

In Chapter 6 the hydrometeorological relationships within the catchment were examined, but a number of problems remain concerning water transfers within the catchment. The main conclusion is that moorland with a mature heather cover is able to absorb and retain large amounts of moisture. Consequently, despite the high precipitation input and humidity of this upland environment, water release as discharge forms a relatively low proportion of total ~~moisture input, more comparable with lowland environments than with~~ more erosive upland catchments.

Runoff affects the translocation and transportation of sediments from the catchment, but the relationships between the variables concerned are complex. In particular, the hysteresis and flushing effects complicate causal relationships. Nevertheless relationships between the independent variable, stream discharge, and the dependent variables of sediment type, were detectable, which allowed the computation of denudation rates. Collected data suggest that mature heather moorland experiences little erosion. The pebble experiment demonstrated very low magnitudes of intra-catchment movement, whereas evaluation of each sediment component revealed minimal losses compared with other environments. Indeed, an examination of potential sediment inputs from outside and within the catchment, suggests that net accretion of sediments may be occurring within moorland environments with a mature cover of heather.

The protective effects of heather may be manifested in the low

association between fluvial and sediment discharge. The lack of a developed drainage net on mature heather moorland, and the lack of associated exposed channels, may result in little erosion, despite high stream discharges. Finlayson (1977) reports low levels of association between fluvial and sediment discharge within the heather-covered catchment of East Twin Brook. From an examination of sub-catchments of Bransdale, Burgess (1976) found that explanation of variance of stream sediment concentrations offered by fluvial discharge decreased as vegetated density increased and drainage density decreased. Hence, mature heather moorland may not respond directly to active processes of hydrometeorological input and stream discharge, but may impede, protect and buffer the system against the erosive potential of these processes.

In terms of catchment hydrology, heather moorland appeared to influence hydrological transfers through effects upon such processes as interception, transpiration, moisture uptake and overland flow, in such a way as to diminish the supply of potentially erosive runoff. From a geomorphological standpoint the heather canopy operates in a similar way, by absorbing and dissipating raindrop energy, which if allowed to operate on the soil surface would encourage soil erosion. The presence of a dense biomass also impedes the transportation of sediments through the catchment.

The protective buffering effect of the vegetation is not consistent throughout the year. Changes in the nature of precipitation inputs and the efficiency of various hydrological processes in Winter encourages greater relative proportions and absolute amounts of runoff, and this enhanced erosivity is reflected in a greater

sediment output.

Collected evidence suggests that Callunetum moorland is a stable hydrological and geomorphological system, buffering the soil surface from the full potential of the processes acting upon the system. Thus, moorland with a mature heather cover releases relatively low volumes of water and sediment. Heather moorland undergoes periodic disturbance by burning. The hydrological, pedological and geomorphological disturbance caused by heather burning practises will be the main theme in subsequent chapters.

CHAPTER 8

SOIL PLOT RESULTS

The investigation conducted on Egton High Moor has been described earlier. This chapter is concerned with pedological changes which occurred within the plots over one annual cycle. Two plots were burnt while a third remained vegetated as a control. Surface level changes were measured using erosion pins while pedological variations were monitored by periodic intensive sampling.

VEGETATION CHARACTERISTICS

As discussed in Chapter 3, the ages of the stands were reliably dated as 15 years old (B. Nellist, pers. comm.). The overall mean vegetation height for the three plots was 36 cm (N = 12) composed of 33 cm for the control plot, and 39 and 36 cm for the mean pre-burn heights on the moderately and intensively burnt plots, respectively (N = 4 on each).

The above-ground biomass of the plots was extremely variable. The dry-weight of 0.5 m² above-ground samples ranged from 487 to 1775 g m⁻² equivalent to 19.48 and 50.21 t ha⁻¹, with a mean of 29.9 t ha⁻¹. Pre-burn means of 22.05 and 35.37 t ha⁻¹ for the moderately and intensively burnt plots were based on 4 random samples taken from each plot. Such figures indicate that considerably more fuel was available for combustion on the intensively burnt plot.

These values represent relatively large amounts of biomass for Callunetum heathland when compared with other reported figures.

Mork (1946) found the dry-weight of above-ground heather biomass to be 14.4 t ha⁻¹ in Norwegian stands, Kayll (1966) reports 15.9 t ha⁻¹ for a 15 year old stand in Kincardineshire, Scotland, while

Robertson and Davies (1965) found values ranging from 3.24 to 29.36 t ha⁻¹ for sites in Northumberland and Scotland. The latter figure, reported for a 15 year old stand in Kincardineshire, is quite similar to the mean biomass found on the 15 year old stand on Egton High Moor.

THE MUIRBURNS

The Northern plot was burned on April 7, 1978 with the Southern plot being ignited on April 24, 1978 (Plates 11a and 11b). The former was burnt at a moderate intensity leaving isolated "leggy" heather stems, while the southern plot was fired more intensively, producing what the gamekeepers refer to as a "clean burn", in which all the heather stems are consumed (Plate 12).

Data collected by the fire monitoring procedures provide evidence for the differences in fire intensity. The pyrometer thermocouple was located centrally within each plot, with the head protruding 2 cm above the surface, to provide data on temperature changes near the ground. The maximum temperature recorded during the moderate burn was 200°C and 250°C during the intensive burn (Fig. 21).

These temperatures, however, refer only to ground-level. Whittaker (1961) and Kayll (1966) have investigated temperature profiles during similar muirburns and found values in the woody crowns to be in the order of 850-900°C.

Applying the multi-variate Index of Fire Intensity, the second burn was more intense, reaching a value of 15,641 g cal sec⁻¹ cm⁻², compared with 4,410 for the moderate burn. The only value available for comparison is that of Kayll (1966) who recorded an intensity value of 7,500 g cal sec⁻¹ cm⁻² during a muirburn in Scotland.

Ancillary measurements suggest that conditions were more conducive for an intense fire on the Southern plot, with greater wind velocities and available fuel amounts, combined with lower soil and vegetation moisture contents (Table 23). One may conclude that the two plots were subject to differing intensities of fire, thus allowing an analysis to be made of the differing pedological responses. Overall responses were evaluated by comparing the results from the control plot with those from the burnt areas.

EROSION PIN SURVEY

The three plots were marked out using wooden pegs and string (Plate 12). Erosion pins, each 40 cm long, were inserted at pre-determined co-ordinates immediately after the respective fires and in the control plot (Appendix I). The pins were re-surveyed one year later and the results are shown in Table 24.

Surface level changes may result from two distinct processes. Physical lowering or accretion of the surface may occur, or changes induced by variations in soil moisture content. Soil wetting may result in surface swelling, as noted on glacio-lacustrine soils in Ontario (Pierce, 1976) or, conversely, dehydration may initiate contraction (Hutchinson, 1980).

Surface level changes are interpreted as being mainly due to the physical lowering or accretion of the surface. The soil moisture content of the plots remained fairly equable and was not appreciably altered by their vegetation status (Fig. 28b).

Soil moisture variations, perhaps over a short time-span, may influence surface level changes, and experiment substantiated this hypothesis. Within the control plot erosion pin J6 recorded the largest surface lowering over the year, at 2.4 cm. The pin was

TABLE 23

Results from the fire monitoring procedures
on the Egton High Moor plots

Variable	Moderate burn April 7, 1978	Intensive burn April 24, 1978
Wind direction	N/NNW	N/NW
Mean wind velocity (m sec ⁻¹)	3.16	3.64
Pre-burn % moisture content of soil	44.23	35.53
Mean rate of fire advance (cm sec ⁻¹)	7.41	11.73
Mean dry-weight of heather and litter (g 0.5 m ⁻²)	551.33	893.29
Fuel consumed (g 0.5 m ⁻²)	431.77	722.86
Fuel consumed as a % of the total available	78.31	80.92
% moisture content of the vegetation	37.79	26.59

TABLE 24

Results from erosion pin survey

Plot	Date 1st survey	Date 2nd survey	Mean surface change (cm)	Standard deviation of change	Volume change (m ³)	Dry-weight of change (g 0.5 m ⁻²)	Dry-weight of change (Kg ha ⁻¹)	Total litter available (g 0.5 m ⁻²)
Control	April 7, 1978	April 24, 1979	+0.021	0.782	+0.084	0.628	24.74	
Moderately Burnt	April 7, 1978	April 24, 1979	-0.327	0.342	-1.3068	9.62	384.89	48.34
Intensively Burnt	April 24, 1978	April 24, 1979	-0.388	0.605	-1.552	11.43	457.10	88.98

inserted through a stand of Cladonia (cf Cossifera) lichen. A sample of lichen and the underlying peat was removed and placed in a plant pot. By inserting a rod through the lichen, changes in surface level could be measured. The results suggest that the surface expands when wet and contracts when dry (Fig. 22).

The correlation coefficient between soil moisture content and surface level change was significant ($r = 0.95$, $P < 0.01$, $N = 8$) indicating that soil moisture content may influence surface level changes over a localised area or over a wetting-drying cycle. The pot results probably indicate greater swelling than would occur under natural conditions, due to the restriction on lateral swelling. However, the generally constant soil moisture conditions suggests that overall, the surface will fluctuate around a stable mean level. Consequently, the erosion pin values have been interpreted as physical changes in the soil surface.

Recorded surface level changes are shown in Figs. 23, 24a and 24b. Mean surface level change recorded on the control plot was an increment of 0.021 cm. This rise may be attributed to the accumulation of litter on the ground surface. Comparison may be made with an accumulation of 0.025 cm reported by Imeson (1971) for 25 year old heather stands in Bransdale.

Within the burnt plots mean surface lowering was 0.33 and 0.39 cm for the moderately and intensively burnt plots, respectively. Lowering may be due to a variety of processes, the most important of which appear to be the removal of ash and loose litter by wind. From the data one may cautiously extrapolate surface changes over larger areas. A rise of 0.021 cm would result in an increased

volume of $2.1 \text{ m}^3 \text{ ha}^{-1}$, while the lowering values would result in losses of 32.67 and $38.80 \text{ m}^3 \text{ ha}^{-1}$ on the moderately and intensively burnt plots, respectively.

Estimates were made of the dry-weight such volumes would possess. Litter samples were collected from the plots using the procedures of Cormack and Gimingham (1964) and Chapman et al (1975b) wherein all litter within randomly selected 0.5 m^2 quadrats were recorded. Sample weights were highly variable, ranging from 90.62 to 33.0 g 0.5 m^{-2} (air-dry weight). The mean weight of 8 samples was 117.81 g 0.5 m^{-2} and the mean depth 4.0 cm implies that a 1 m^3 mass of air-dry litter would weigh 11.78 Kg . Thus, one may calculate a dry-weight gain of 24.74 Kg ha^{-1} on the control plot and losses of 384.9 and 457.1 Kg ha^{-1} on the burnt plots (Table 24).

Accumulation on the control plot was over the annual cycle and thus the 24.74 Kg ha^{-1} gain may be interpreted as annual litter productivity. This is low when compared with the figures reported by Cormack and Gimingham (1964) who found litter productivity for sites in Northumberland and Scotland to range from 59.6 to 712.4 Kg ha^{-1} . Forrest and Smith (1975) found litter productivity to vary between 750 and 1220 Kg ha^{-1} , with a mean of 902.5 Kg ha^{-1} , for sites in Cumbria. However, both sets of values are of gross productivity, measuring actual litter release from heather. The Egton values represent net productivity, as some litter may be lost through removal by wind and through humification (Chapman, 1979). The published values reveal great diversity in heather litter productivity, influenced by numerous factors including the technique of measurement (Chapman et al, 1975a), the microclimate, nutrient status and moisture conditions (Forrest and Smith, 1975).

Litter losses reported for the burnt plots appear to have been caused by wind, the remaining litter and ash being highly susceptible to deflation processes, which have been observed on several occasions. Similar observations have been made on Dorset heathlands by Chapman et al (1975b). No overland flow or active rill systems were observed on the burnt plots. Hence, the most likely method of removal was by wind.

Comparing the Bransdale data, reported by Imeson (1971), with that from the Egton sites, provides further evidence for the importance of wind as a transporting agent. Imeson measured the mean annual surface lowering of burnt areas to be 0.95 cm, this being some three times greater than that observed on the Egton plots. Active fluvial erosion appears to be responsible for the surface lowering in the Bransdale experiment, particularly through the headward extension of gully systems onto recently burnt areas. One may tentatively suggest that the difference between the Egton and Bransdale results is due to active fluvial erosion in the case of the latter.

Estimated losses from the intensively burnt plot are higher than those from the moderately burnt plot. Theoretically, the intensive fire should render the ground surface more liable to wind erosion, liberating more ash and removing all shelter. However, it is difficult to conclude if these theoretical considerations are operative as the observed differences may be due to original variations in the litter biomass.

The estimated litter removed represents only a small portion of the total available litter. Of the mean $48.34 \text{ g } 0.5 \text{ m}^{-2}$ of litter available on the moderately burnt plot ($N = 4$) only an estimated

9.62 g 0.5 m^{-2} , or 20%, was removed. On the intensively burnt plot with 88.98 g 0.5 m^{-2} litter available, an estimated 11.43 g 0.5 m^{-2} , or 13%, was removed. Hence, although nearly twice as much litter was available for removal from the intensively burnt plot compared with the moderately burnt plot, the amount of litter actually removed was only marginally greater, and a smaller proportion of the total available. This suggests that the competence of the wind to transport litter sets the limit on litter removed and the availability of litter exceeds the wind's transporting capacity. The ability of the wind to cause erosion will be discussed more fully in Chapter 10, with observations on wind velocity recordings, and soil particle movement on Sneaton High Moor.

Litter losses reported for the burnt plots must not be regarded as net losses from the ecosystem. One might expect that the litter would be removed by the wind, redistributed, and deposited in adjacent areas. However, an unknown quantity may leave the ecosystem completely, by a variety of pathways. Where the area extent of the heather stand is small net litter loss may be high as the litter is transported to other vegetation systems. Such losses may be particularly high on the relatively small patches of heather, as found on the Dorset heathlands (Chapman, 1970). Losses may be high on the burnt edges of Calluna dominated heathlands. Litter deposited within actively eroding areas may be removed from the ecosystem by streams.

The possibility of a relationship between surface level change and other environmental variables was investigated. Imeson (1971) has suggested that litter accumulation is positively correlated with vegetation height and this hypothesis was tested in the

current investigation, but the degree of association with surface level changes was not significant ($r = 0.29$, $N = 14$).

Slope conditions might influence surface changes, but the nature of the relationship would be affected by processes acting upon the surface. Morgan (1979) suggests that the erosivity of surface water increases with slope. However, wind velocity, and thus erosivity, might be expected to decrease, with increasing slope (Coutts et al, 1968).

To test the hypothesis that slope angle might influence surface changes, the slope angle on both sides of each erosion pin was measured using a 50 cm-long pantometer centred on the pin. The correlation coefficient between slope and surface change was again insignificant ($r = 0.29$, $N = 45$). However, since no evidence was found for surface wash, one might suggest that wind is the dominant transporting agent. The evidence does not support the suggestion of Coutts et al (1968) that wind erosivity is inversely related to slope angle.

Discussion has so far concentrated on the mean values, but surface level changes were highly variable, with losses and accumulations being recorded within each plot. Analysis of variance of surface change data did not yield a significant difference at the 0.05 confidence level (F ratio = 1.38, $N = 45$). Thus, the variability of change within each plot exceeded the differences between plots. Hence, simple statements on accumulation under heather stands and losses on burnt ground is a gross simplification. Rather, there is a complex pattern of accumulation and loss on each moorland type, with an overall tendency for accumulation on heather covered moorland and loss on burnt moorland. The complex pattern of change

revealed by the erosion pin survey was interpolated into contour maps using the SYMAP Computer Program (Figs. 25, 26a, 26b).

SOIL RESULTS

Pre-burn soil characteristics were measured by removing samples on March 14 and 16, 1978. Soil samples were taken immediately after the muirburns and at 6 month intervals over the following year. The design of the soil sampling programme is described in Chapter 3 and Appendix I.

The spatial variability of soil characteristics makes the separation of temporal trends difficult to identify. Analysis of Variance tested the variability of each soil property, and none of the F-ratios were significant (Table 25). T-tests were carried out for each soil property, both between plots and for each plot at different points in time. Significant differences between soil organic contents for the control and moderately burnt plots ($T = 2.56$, D.F. = 12, Prob. < 0.05) and the control and intensively burnt plot ($T = -2.18$, D.F. = 12, Prob. = < 0.05) were found. Thus, the variability of individual soil characteristics within any particular plot exceeds the differences in the means of each individual plot.

The lack of differences between plots relates to the inherent stability of soil properties, whether disturbed or undisturbed. The data do allow some relationships to be detected, which are discussed below. Although a great deal of scatter exists in the data, the plotting of grand mean values does indicate some temporal trends, particularly in soil reaction and organic matter. The grand mean for any soil characteristic is the mean result of 4 samples each comprising 4 sub-samples. As discussed in Chapter 3

TABLE 25.
Analysis of Variance¹ of Soil Characteristics

Soil Characteristic	No. of Groups	No. of Observations	F-Ratio
Soil moisture (%)	3	39	0.12
Coarse fraction (%)	3	39	0.49
Fine fraction (%)	3	39	0.17
Sand fraction (%)	3	39	0.15
Silt fraction (%)	3	39	0.11
Clay fraction (%)	3	39	0.56
Organic fraction (%)	3	39	3.30
Soil reaction (pH)	3	39	0.18

1. Critical F-Ratio (with 2 and 36 D.F.) = 8.8 (at 0.05 confidence level).

at least 16 samples were taken from each plot. Thus, each reported value is a grand mean on top of a hierarchy of observations.

THE CORRELATION MATRIX

Since soil properties appeared to be stable, irrespective of treatment, changes which occurred may be related to other factors. In the following discussion, the statistical associations between soil properties are examined as a preliminary step in the investigation of inter-relationships and correlation coefficients are shown in Table 26. Textural variables were inter-correlated, as variables are defined in terms of other textural variables. Correlation coefficients, significant at the 0.05 confidence level, were found between soil pH and both soil moisture content and clay content.

Although correlation coefficients are not significant using simple correlation this does not preclude the possibility of some hidden relationships. Hence, partial correlation produced a total of 243 valid coefficients which allowed the construction of a correlation matrix (Fig. 27). Again, the textural variables are highly inter-related. However, relationships were observed which were not observed using simple correlation, which are discussed in the relevant sections.

SOIL COLOUR

Soil colour is a subjective phenomenon, but attempts to standardise colour have been made with the use of Munsell colour notation (Pendleton and Nickerson, 1951). The possibility of 'muirburn' initiating colour change was investigated. Theoretically, the loss of organic matter by burning may induce a lighter colour, as the organic matter is mainly retained within the black humus

TABLE 26

Correlation coefficients between
the soil properties of the Egton Moor Soil plots

moisture (%)	Significant at 0.05 confidence level		Significant at 0.01 confidence level		N = 39	pH	% organic matter	% coarse fraction	% fine fraction	% sand	% silt	% clay
	moisture	pH	organic matter	coarse fraction								
pH	<u>0.38</u>	-0.26										
% organic matter	-0.09	0.058	-0.14									
% coarse fraction	-0.13	-0.05	0.15	<u>-0.99</u>								
% fine fraction	-0.11	-0.24	0.16	-0.09	-0.09							
% sand	-0.14	0.19	-0.19	-0.11	0.11					<u>-0.99</u>		
% silt	-0.12	<u>0.37</u>	0.13	0.09	-0.08					<u>-0.34</u>	0.19	
% clay	0.21	0.16	-0.25	0.30	-0.31					0.10	-0.11	0.05
Soil depth (cm)	-0.04											

layer (Chapman, 1970). Such a negative association between Munsell Soil Values and organic matter has been confirmed by Krishna Murti and Satyanarayana (1971) ($r = -0.52$, $N = 26$), with reference to soils of the Malwa Plateau, India. The possibility of organic matter loss consequent upon burning has already been noted in the literature review (Chapter 1) and this may be detected by an increase in Soil Colour Values.

Fig. 28a shows the mean Munsell Values for the plots over the year (March 1978 - April 1979) and no overall pattern of change is detectable. The soils were all very dark, the highest individual colour value being 4, and thus may be explained by the high humus content. Six of the samples were defined as 'black' (10R/2.5/1).

Spatial variation in soil colour probably explains the colour changes. Most samples had a reddish tinge, related to the red/yellow colour of the Estuarine parent material. "Dark reddish brown" (SYR/2.5/2) was the dominant colour and 11 of the samples belonged to this group. The others were "very dusky red" (2.5 YR/2.5/2) (6 samples) and "dark reddish grey" (10 R/3/1) (4 samples). One sample each belonged to the group "dusky red" (2.5 YR/3/3), "very dark red" (5 YR/1/3) and "reddish black" (10 YR/2.5/1).

SOIL MOISTURE

Studies on the affect of forest fires on soil moisture have reported a decrease in moisture holding capacity consequent upon burning (Ahlgren and Ahlgren, 1960; Taber and Murphy, 1971). However, little data have been collected on the response of soil moisture to muirburn.

Fig. 28b displays stable soil moisture conditions on the three plots, irrespective of treatment. Rennie (1957) found soil moisture content to be stable throughout the annual cycle on undisturbed heather moorland, and this has been confirmed within unburnt heather moorland by neutron probe recordings undertaken by the Institute of Hydrology on Sneaton High Moor (J. Roberts, pers. comm.), which is further reported in Chapter 10. The soil moisture content on the control plot was extremely stable, varying little at each sampling period. However, neither of the burnt plots displayed any reduction in soil moisture retention consequent upon burning. Lloyd (1968) reached a similar conclusion, with no evidence for soil moisture deterioration in burnt grassland communities within the Peak District.

The stability of soil moisture conditions within the plots clearly suggests the importance of the surface organic layer in retaining moisture. Textural analysis has demonstrated the arenaceous nature of these soils, indicating poor moisture retentative properties, due to the large interstitial pore sizes (Brady, 1974). A number of studies have confirmed this point, including investigations on soils of the European U.S.S.R. (Grin and Nazarov, 1967), Zambia (Maclean et al, 1972), Pennsylvania (Peterson et al, 1968), North Dakota (Rivers and Shipp, 1972) and Warwickshire (Salter and Williams, 1967). Thus, one might suggest that the clay-organic complex maintained stable soil moisture conditions within the plots. No association was found between soil moisture content and either organic matter or clay content, although several writers have observed such an association (Salter and Williams, 1963; Peterson, 1968; Maclean et al, 1972; Western, 1972). Most agree on the importance of the surface organic

horizon as a buffer against soil deterioration within heathlands (Whittaker, 1961; Whittaker and Gimingham, 1962; Allen, 1964). Thus, provided muirburn does not destroy the surface organic layer, moisture conditions appear to be fundamentally stable.

SOIL ORGANIC MATTER

Organic matter forms an important component of heathland soils, (Chapman, 1970), being concentrated in the upper 6 cm of the solum, the surface 'O' horizon as described by Gimingham (1971). The main components include woody material in the root systems of Calluna plants and the greasy, black, raw humus which incorporates decayed vegetation and a variety of organic acids. Soil flora (Brown, 1958; Sewell, 1959; Latter et al, 1967) and fauna (Murphy, 1953; Gimingham, 1960; Cragg, 1961) form important additional constituents.

An attempt was made to evaluate the general amounts of organic matter present. A monolith of soil, measuring 25 by 25 cm and 10 cm deep, was removed from sites adjacent to the plots. The vegetation cover and heather litter were removed and the monolith was air-dried for 24 hours to determine the dry-weight. Subsequently, the block was crushed and a sub-sample of 200 g removed for analysis by loss-on-ignition.

The sample was ignited at 375°C for 16 hours and a weight loss of 39.2% was recorded, which is equivalent to 80 g for the 2.04 Kg block. This result would extrapolate to 128.14 x 10³ Kg ha⁻¹ of organic matter in moorland soils.

The high organic content probably relates to the large amounts of heather roots present in the soil. The soil organic content from

the soil plots is considerably less than found in the block, with a mean of 16.51%. These results are based on fine-earth fraction samples where most of the woody remains had been removed. If one assumes the weight of the block to be representative, then a soil organic content of 16.51% would extrapolate to $53.93 \times 10^3 \text{ Kg ha}^{-1}$ of soil organic matter.

The results may be compared with those of Chapman (1970, 1979) who found the soil organic content of Dorset heathland to be $140 \times 10^3 \text{ Kg ha}^{-1}$, and suggested that about half of this was composed of plant roots. Assuming the difference between the soil plot sub-samples and the monolith represents plant roots, then $74.21 \times 10^3 \text{ Kg ha}^{-1}$, or 58% of heather moorland soil organic matter, is accounted for by rooting systems.

Organic matter is clearly present in large amounts in heathland soils though the Egton profiles appear to possess slightly lower amounts than their Dorset counterparts. Plant roots form a large component of organic matter, though their overall contribution appears higher on the soil plots than on the Dorset heathlands.

Work on the response to burning has concentrated on the effect of fires on forest soil organic matter (Austin and Baisinger, 1955; Ahlgren and Ahlgren, 1960; Taber and Murphy, 1971; Viro, 1974). An observed reduction in organic matter may be partly explained by oxidation induced by fire and the removal of biomass which may have introduced organic matter into the rhizosphere through biogeochemical cycling.

Fig. 29a demonstrates that organic matter values remained stable irrespective of treatment. Neither fire destroyed the surface

organic horizon composed of heather litter in various stages of decay and raw humus. Evidence suggests that the surface 'O' horizon is an effective insulator against temperature changes during muirburn. Whittaker (1961) found that temperature variations at a depth of 1 cm were up to 300°C less than those recorded at the surface. Hence, the potential depth of oxidation is very shallow, and Whittaker's conclusion is confirmed by evidence from burnt grasslands in the Peak District (Lloyd, 1968) and forest soils in Zambia (Trapnell et al, 1976).

The trends on Fig. 29a suggest that any detrimental effects of burning are masked by seasonal changes, irrespective of treatment. A general trend of increasing organic matter content between Spring and Autumn, followed by a subsequent decrease is apparent, and this may be related to seasonal variations in floral and faunal activity.

The increase in organic matter between March and October probably reflects warmer Summer temperatures. Grace and Woolhouse (1971) report an increase in heather photosynthesis over Summer, from a low in May of $15 \mu\text{g CO}_2 \text{ g}^{-1} \text{ min}^{-1}$ to a peak in July of $78 \mu\text{g CO}_2 \text{ g}^{-1} \text{ min}^{-1}$. Increases in root activity would further increase organic inputs into the soil. Chapman (1979) found that heather roots increased levels of organic carbon in the soil from $50.4 \text{ g m}^{-2} \text{ C}$ in January to $132.1 \text{ g m}^{-2} \text{ C}$ in August. Similarly, Gupta and Rorison (1975) report a Summer maximum of organic nitrogen and phosphorus in moorland soils while Robinson (1971) found a Summer maxima both in the release of phytotoxins from heather litter and endotrophic mycorrhizal activity. Thus, enhanced Summer floral activity would tend to increase the organic content of heather moorland soils.

Similar processes have been observed for soil fauna. Cragg (1961) suggests that the complexity and development of moorland faunal communities are relatively low. In discussing metabolic activity, defined as $\text{mg O}_2 \text{ m}^2 \text{ hr}^{-1}$ at 13°C consumed by soil fauna, he reports that rates are 6 times greater on Juncus moor and alluvial grassland and 12 times greater on limestone grassland than on Calluna moor, assertions confirmed by Latter et al (1967). Cragg estimates that soil fauna in Calluna moor amounts to approximately 30 g m^2 , which, assuming the mean Egton organic figure to be correct, amounts to only 0.23% (by weight) of total organic matter. However, seasonal variations in soil fauna populations may influence changes in soil organic matter.

Soil fauna require adequate moisture and warm temperature (Block, 1966). Combinations of the two encourage Spring and Autumn population maxima, decreasing in Summer and Winter, due to insufficient moisture and low temperatures, respectively. This basic bimodal pattern has been confirmed for a number of heather moorland fauna. Murphy (1953) reports a November peak in arthropod populations, at 570,000 individuals per m^2 while Block (1966) reports a similar trend in moorland mite populations. A similar situation is reported for moorland populations of Acari and Collembola (Wood, 1967), Coleoptera (Penney, 1966), Diptera (Freeman, 1967) and Enchytraeidae (Springett, 1970). Hence, the Autumn peak in soil fauna populations may partly explain the higher organic contents at that time although this will be partially offset by the respiration of organic substrates by the fauna themselves.

The soil micro-arthropod populations of the Egton High Moor plots have been investigated by R. Brown (pers. comm.). Soil cores,

measuring 10 cm in diameter and 10 cm deep, were removed from both the control and moderately burnt plots. 15 cores were removed from each plot in July 1979 and January 1980, giving a total of 60 samples. Each core was then divided into two 5 cm long segments and the micro-arthropod population of each sub-sample was determined microscopically after extraction using the Berlese-Tullgren funnel method (Macfeyden, 1961; Wallwork, 1970; Southwood, 1978). The results are shown in Table 27.

Several points deserve comment. Firstly, the evidence confirms other observations on the concentration of moorland soil fauna in the topsoil. On the control plot some 65% and 54% of the measured population are within the top sub-samples for the first and second surveys, respectively. On the burnt plot 60% of the faunal population were within the top sub-sample at the first survey. At the second survey the situation had reversed, with only 24% of the total population in the topsoil sample. This reversal will be discussed in relation to seasonal trends in soil fauna populations.

Various workers have noted the concentration of moorland fauna in the topsoil. Murphy (1953) reports that 96% of soil arthropod populations were in the top 6.4% of the soil. Cragg (1961) found Nematode populations concentrated in the uppermost 6 cm, while Block (1966) found Acari concentrated in the uppermost 3 cm. Wood (1967) reports Acari and Collembola as being most prevalent in the top 4 cm of the soil, further supported by Springett et al (1970) with respect to Enchytraeidae.

A second point is the seasonal variation in micro-arthropod populations. The total micro-arthropod population of the heather

plot fell from 27,525 per m² in July 1979 to 18,860 per m² in January 1980, which represents only 68% of the July population. The decrease in the burnt plot is even more dramatic, from 10,565 per m² to 4,830 per m² over the same time period, a fall of 55%. These measurements confirm the general notions on seasonal variations in soil fauna populations discussed previously.

While no obvious differences were detected in total soil organic matter between the plots, distinct differences may be observed in the soil micro-arthropod populations. At each sampling time the population of the heather plot exceeded that of the burnt plot, both in total numbers and for each sub-sample. Thus, in July 1979 the total population of the burnt plot was 38% of that for the control plot, falling to 26% by January 1980.

The more extreme and variable micro-environment above the burnt ground may explain these differences. For instance, Collembola require relative humidities in excess of 90% for normal survival (Cragg, 1961). The high relative humidities under heather (Gimingham, 1964, Barclay-Estrup, 1971) allow the survival of Collembola, whereas the desiccated nature of burnt ground would prove inimical. Such differences are evident in the measured Collembola figures. In July 1979 the population of the burnt plot was only 29% of that on the control plot, the corresponding value in January 1980 was 27%.

The tendency for burnt ground to experience more intense and prolonged frost than vegetated areas is also detrimental to soil fauna, and temperature differences are given further consideration in Chapter 9. Nematodes are particularly susceptible to frost (Cragg, 1961) and their number were reduced from 40 to 0 per m²

TABLE 27

Variations in soil micro-arthropod populations²
on the Egton High Moor soil plots (Numbers per m²)

GROUP	CONTROL PLOT						BURNT PLOT					
	July 1979		January 1980		July 1979		January 1980		July 1979		January 1980	
	0-5 cm	5.1-10 cm	0-5 cm	5.1-10 cm	0-5 cm	5.1-10 cm	0-5 cm	5.1-10 cm	0-5 cm	5.1-10 cm	0-5 cm	5.1-10 cm
Acarl (mites)	4680	2760	3100	2670	1950	2010	620	1700	2010	620	1700	1700
Diptera	600	20	0	0	20	5	5	0	5	5	0	0
Coleoptera	240	60	80	25	65	25	0	0	25	0	0	0
Protura	20	0	0	0	0	15	0	30	15	0	0	30
Chilopoda (centipedes)	120	85	95	80	360	15	0	45	15	0	0	45
Enchytraeid worms	2000	4600	1800	4000	190	480	40	680	480	40	0	680
Nematoda	320	450	300	460	0	40	0	0	40	0	0	0
Collembola	9870	1700	4800	1450	1760	1650	480	1230	1650	480	1230	1230
TOTAL	17850	9675	10175	8685	6325	4240	1145	3668	4240	1145	3668	3668

between July 1979 and January 1980, on the burnt plot. On the heather plot the numbers remained fairly stable at 770 and 760 per m² over the same period.

Freezing conditions may have influenced the vertical movement of Enchytraeid worms, as they can move deeper into the profile to escape low temperatures (Springett et al, 1970). In each case (topsoil and subsoil) Enchytraeidae were more prevalent in the deeper sub-sample, but this is particularly marked on the burnt ground in Winter, with only 6% of the population in the uppermost 5 cm of the soil.

The fall in soil faunal populations may partly explain the fall in total soil organic content between Autumn and Spring (Fig. 29a). Cooler temperatures also impede floral and biogeochemical activities, and so result in a reduction in organic contents. The fall in mean soil organic levels was particularly marked on the intensively burnt plot which may reflect more extreme climatological conditions. This theme is discussed in more detail in Chapter 9.

SOIL REACTION

Temporal changes in soil reaction were monitored (Fig. 29b), and within the control plot acidity decreased over the year, but less dramatically than on the burnt plots. Between the third and fourth surveys mean soil acidity began to increase on the intensively burnt plot.

These changes may be related to a number of factors. The correlation matrix demonstrates associations between the dependent variable, soil pH and the independent variables, moisture content, clay content, organic content, coarse fraction and the fine fraction (Fig. 27).

In an attempt to investigate the relative importance of these variables, step-wise multiple regression analysis suggests that moisture, clay content and organic matter affect pH levels. Soil moisture content explains 14.2% of soil pH variance. Incorporation of percentage clay content increases the explanation to 23.5%, which rises to 31.0% with the incorporation of organic matter. Addition of the arenaceous fractions only improves the explanation by 0.69% and consequently these are excluded from the equation given below :-

8(1)

$$\text{Soil pH} = 0.0062 (M) + 0.062 (C) - 0.0122 (O) + 3.331$$

$$\text{Multiple } r = 0.56$$

$$N = 39$$

where M = % soil moisture content

C = % clay content

O = % soil organic matter content

The possible affects of these three variables on soil reaction are given further consideration. Moisture content may influence soil pH in two ways. Firstly, soil water incorporates soluble salts held on and within the system and secondly the pH of rainfall inputs may affect soil reaction through its affects upon soil moisture pH. The affects of burning on the volatisation and liberation of salts held within the biomass have already received attention (cf Chapter 1). Consequently, soil moisture will contain these water-soluble salts which, being relatively alkaline, will reduce soil acidity.

Heather litter samples were ashed (850°C for ½ hour) and a mean pH of 8.0 was measured (N = 2). According to a laboratory

simulation of heather fires by Allen (1964), the elements K, Ca, Mg and P contained within heather are converted into potassium chloride (KCl), calcium chloride, hexahydrate ($\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$), magnesium sulphate ($\text{Mg SO}_4 \cdot 7 \text{H}_2\text{O}$) and di-sodium hydrogen orthophosphate ($\text{Na}_2 \text{H PO}_4$), respectively.

The pH of these salt solutions was measured, ranging from 5.1 for Mg and K, to 6.7 for Ca and 8.3 for P, with an overall mean of 6.3. Although only one solution ($\text{Na}_2 \text{H PO}_4$) was actually alkaline, they are all relatively less acidic than heathland soils generally, and could contribute to an increase in pH. Solubility may be further increased by the higher soil temperatures experienced by burnt moorland (Delaney, 1953), a topic which will be examined in more detail in Chapter 9.

Hem (1970) has discussed the general acidity of precipitation, resulting from the absorption of CO_2 and SO_4 to form the dilute acids H_2CO_3 and H_2SO_4 , respectively. Likens et al (1976) and Galloway et al (1976) have noted the complex acid composition of rainfall in the north-eastern U.S.A. and stressed the importance of H_2SO_4 and HNO_3 in contributing to acidity levels.

A review of the literature suggests that rainfall pH is less acid than the soils present within the soil plots. Tamm (1953) measured rainfall pH in the range 4.3 to 5.9 in eastern Sweden while Egner and Eriksson report pH values ranging between 3.9 and 6.9 in Scandinavia. Within southern Norway the reported range is from 4.3 to 5.1 (Wright and Henriksen, 1978).

Within the British Isles rainfall pH is generally less acid than the moorland soils under discussion. Gorham (1955) reports rainfall pH values varying between 4.5 and 5.2 in the Lake District,

while Cryer (1976) quotes values between 4.1 and 6.5, with a mean of 4.9 (N = 79) in upland Wales. Weekly precipitation samples were collected from Wintergill, between July 1979 and June 1980, yielding pH's varying between 4.4 and 5.5, with a mean of 4.8 (N = 36).

Precipitation is usually considered to be a factor promoting soil acidity, due to ion exchange and the leaching of bases, particularly Ca and Mg (Fisher et al, 1968), and such increased acidity may lead to a reduction in biomass productivity (Whittaker et al, 1974). However, in the case of the soil plots, as rainfall pH greatly exceeds the soil values, one may tentatively suggest that precipitation may be reducing soil acidity levels. Furthermore, the potential ionic exchange and leaching of bases by acid precipitation is buffered by the release of ammonia during the humification process (Carrol, 1962). The relationship between the two variables, soil reaction and soil moisture, is shown in Fig. 30a.

The relationship between clay and soil pH may be explained by the colloidal nature of clay micelles (Pitty, 1979). Moisture is attracted to the clay micelle, as H^+ ions act as a bond between the water molecule and the clay surface. Consequently, the solute bearing water is attracted to the clay particle. Brady (1974) discusses the unsatisfied valences of Si and Al ions at the broken edge of the clay micelle. The overall charge of the clay micelle is low, due to the strong bonding of hydrogen ions at low pH (Pratt, 1961). Consequently, the cation exchange capacity (CEC) of clay particles in an acid environment is low. Brady suggests a value of 2-3 meq/100 g for clay particles in such conditions.

The acidity of heather moorland soils is largely attributed to the secretion of organic acids from heather litter (Grubb and Suter, 1971). Thus, the removal of organic matter should enable the measurement of the potential CEC of clays. Sub-samples were taken from the Egton Moor soils. An integrated sample was taken from each plot, while a fourth sample was composed of a mixture of samples from the three plots. After preparation the clay separates were removed by sedimentation (cf. Appendix IV) and the CEC measured (Appendix V).

The CEC of the inorganic clays were very high (Table 28) expressing the potential of the clay for cation exchange, but this would not be realised in an acid environment. However, in natural conditions a sufficient charge may be available to attract certain cations. The strength of attraction is determined by the cation's valency, so that Ca^{++} will be most strongly attracted, followed by Mg^{++} , K^+ and Na^+ . The relationship between clay content and soil pH is shown in Fig. 30b.

Theoretically, the organic colloids should exert a stronger attraction to cations, and a positive association between CEC and organic matter has been noted in desert soils (Western, 1972), soils in Ohio ($r = 0.74$, $N = 28$) reported by Wilding and Rutledge (1966) and Maryland soils ($r = 0.73$, $N = 57$) by Wright and Foss (1972). The CEC of organic colloids is in the order of 200 meq/100 g (Brady, 1974). Reported organic fraction CEC of 200, 316 and 201 meq/100 g for Coastal Plain, Piedmont and Appalachian soils of Maryland are in broad agreement (Wright and Foss, 1973). Organic colloids exert a strong negative charge through the unsatisfied valences of the O^- and CO^{--} ions (Brady, 1974).

TABLE 28

Cation Exchange Capacity values for the Egton High Moor soil plots

Plot	Cation Exchange Capacity of fine-earth (< 2 mm) fraction (meq/100 g)	Cation Exchange Capacity of inorganic fine-earth (< 2 mm) fraction (meq/100 g)	Cation Exchange Capacity of clay (< 2 μ) separates (meq/100 g)
Control	45.71	5.82	94.4
Moderately Burnt	36.30	4.46	142.4
Intensively Burnt	50.64	3.60	121.6
Mixture of all Samples	50.77	4.80	152.0
Mean	45.85	4.67	127.6

The importance of organic colloids to the cation exchange capability of Egton Moor soils was demonstrated by laboratory tests. Fine-earth fractions were taken from the bulked samples from each plot and from a mixed sample of all the plots and the CEC subsequently determined. Organic matter in replicate samples was oxidised, using H_2O_2 , and the analysis repeated on the inorganic fine-earth component.

The results demonstrate the importance of organic matter in the cation exchange capacity of the Egton Moor soils (Table 28).

The CEC of the organic matter was of the order of 40-50 meq/100 g. However, the inorganic soils had a CEC of only 4-5 meq/100 g. The mineral soil results compare favourably with those reported by Brady (1974) for clays in an acid environment and with those reported by Chapin et al (1979) for soils underlying

Eriophorum vaginatum tussocks in Alaskan tundra. The organic matter within the soil possessed high exchange capabilities, which were crucial for the nutrient status of Eriophorum vaginatum tussocks.

One may conclude that organic matter retains the cations released through burning, providing further evidence of the crucial role of the surface organic horizon. If the fire does not damage or destroy this horizon then cations will tend to be retained within the humus by the organic colloids. Subsequently, nutrients may be taken up by the regenerating vegetation, but if the organic layer is destroyed, the colloidal properties will also disappear. Hence, the retention of nutrients will be less, exposing them to translocation into the mineral soil. Since Calluna is a very shallow-rooting plant (Rennie, 1957; Boggie et al, 1958) leaching will quickly remove these nutrients from the biogeochemical cycle.

Evidence presented so far suggests a positive relationship between soil reaction and soil organic matter. However, the correlation matrix demonstrates a negative relationship between the two variables. The attraction of alkaline salts to organic colloids occurs in an acid environment. Acidic chelates, such as fulvic and humic acid, secreted into the humus from Calluna litter, would neutralise alkaline solutions within the humus. Hence, there is a negative correlation between soil pH and soil organic matter.

Considering the relationships discussed one may begin to interpret these soil reaction trends. The multiple regression equation was used to predict soil reaction. The equation evaluates mean soil moisture content, clay content and soil organic content recorded at the soil sampling period. In each individual case there was a positive residual. Hence, soil reaction was always higher than predicted and may be explained by the disturbance induced by burning.

Contrary to trends suggested in the literature (Grubb and Suter, 1971), soil pH rose throughout the year on the control plot.

Taking the multiple regression equation into account soil reaction was 0.14 pH units higher than predicted after 6 months and 0.33 after one year. A plausible explanation is that the large amounts of smoke which descended upon the control plot during the moderate burn deposited volatised salts on the soil surface, which may have gradually altered the pH.

On the burnt plots soil pH increased more than predicted. Within the moderately burnt plot the residual pH was 0.17 greater than predicted after 6 months, rising to 0.30 after one year. The residual increase was greater on the intensively burnt plot. The

first six months showed a residual of 0.67, which fell to 0.48 over the year.

The greater positive residual found on the intensively burnt plot may be explained by two factors. Greater amounts of surface biomass were available for consumption by the fire on the intensively burnt plot (Table 23). Thus, potentially more salts were available for liberation than on the moderately burnt plot. As already established, the fire on the intensively burnt plot consumed considerably more biomass than on the other plot. Consequently, the salts liberated per unit mass may have been greater.

The phenomenon of increasing soil pH consequent upon muirburn has been observed by several workers (Elliott, 1953; Allen, 1964). Mellor (1978) reports an increase in soil pH following the extensive Glaisdale fire of 1976. Soil reaction ranged from 3.1 to 3.4 on undisturbed moorland to between 4.2 and 4.9 on "badly burnt soils". The Egton High Moor soils did not demonstrate the same order of soil pH increase as found on Glaisdale. This is probably a reflection of differing intensities of burning, extremely intense burning on Glaisdale compared with the less intense, controlled burning on Egton High Moor. While the evidence of changes in soil pH within the plots are not conclusive, the experiments do demonstrate that soil pH changes consequent upon burning are related to a number of variables. Other workers have considered the general changes in soil reaction following burning. However, these changes are in themselves complex and partly related to variables other than the burn itself, such as soil moisture content, organic content and clay content.

Considering the inter-relationships discussed one may construct a

tentative conceptual model for the factors influencing soil reaction within heather moorland. From a hierarchical viewpoint three main groups of variables, each composed of subsets, may be discerned. These are the muirburn itself, soil moisture and the clay-organic complex. These variables interact with each other and with soil reaction (Fig. 31).

SOIL TEXTURE

The Egton High Moor soils are classified as sandy stagnohumic gleys (Avery, 1973), consisting of a raw humus layer overlying a thin sandy horizon in which the fine fraction is predominantly fine sand. The soils are generally coarse (Fig. 32a) varying between 6.9 and 67.8% of the total dry weight of the soil samples.

The fine-earth fraction is mainly composed of sand (Fig. 32b). Sandy loams account for 28 of the 39 samples, the remainder comprising 1 sand-silt loam, 7 loamy sands and 3 sands (Avery, 1973).

The composition of the fine-earth fraction is variable. Sand ranged from 42.9 to 95.2%, silt varied between 2.6 and 55.0% with clay representing only a very small component, of less than 6%. According to the correlation matrix clay is positively associated with organic matter. Although the correlation does not emerge in a simple analysis, a significant correlation coefficient emerges when the effects of moisture, pH, fine-earth fraction, coarse fraction, sand and silt are individually controlled. The relationship is possibly explained by the chemical combination between humified organic matter and the clay silicate molecule (Wallwork, 1970).

As noted in Chapter 3 the texture of the Egton High Moor soils accords with that reported for the Howard Series (Bendelow and Carrol, 1976). A representative bulked profile of the Series was composed by weight of 86.5% sand, 8.5% silt and 5% clay. Similar soil textures are reported on the Dorset heathlands (Chapman, 1970), where sand content varied between 79 and 97%, silt between 3 and 19.5% and clay between 0 and 1.5%.

Neither the coarse fraction, fine-earth fraction or its constituents demonstrate any clear temporal trend (Figs. 32a, b; 33a, b, 34). Ahlgren and Ahlgren (1963) suggest coarsening of the soil may ensue following vegetation-burning, while with regard to heather burning, Curtis (1965) and McVean and Lockie (1969) agree that textural changes may occur. Such changes appear to be related to any one, or a combination, of factors. Severe fires, burning on steep slopes or periodic burning over a long period of time, may all encourage textural changes.

Active surface changes within the plots appear to be related to the effect of wind. Since the surface organic layer was not removed by fire, the mineral soil was not subjected to the erosive power of the wind. Textural variations are probably explained by spatial variations in soil texture. As such they provide further evidence of the spatial heterogeneity of soils, as noted by Beckett and Webster (1971), Reid (1972), Arnett (1974) and Collins (1976).

SOIL MAGNETISM

The magnetic measurements of the Egton soils did not reveal any systematic differences in the magnetic properties of burnt and unburnt soils (F. Oldfield, pers. comm.). The mean magnetic susceptibility of the unburnt soils was $3.36 \times 10^{-6} \text{ cm}^3 \text{ g}^{-1}$

(N = 9) compared with $2.03 \times 10^{-6} \text{ cm}^3 \text{ g}^{-1}$ (N = 8) for the burnt samples. Neither revealed any systematic differences in relation to burning intensity. Mean magnetic susceptibility of the moderately burnt samples was $1.85 \times 10^{-6} \text{ cm}^3 \text{ g}^{-1}$ (N = 4), compared with $2.20 \times 10^{-6} \text{ cm}^3 \text{ g}^{-1}$ (N = 4). Simple and partial correlation analysis did not reveal any significant associations with other soil properties.

Various hypotheses may be postulated to explain the lack of any systematic differences between burnt and unburnt soils. The land management regime of the area is such that any particular area will be burnt at regular intervals. Consequently, the soils may have already been oxidised by previous burns. Furthermore, little iron may be present for conversion in the burning process. Magnetite and haematite were identified within the samples (F. Oldfield, pers. comm.) although Bendelow and Carrol (1976) report a low ferric content for the Howardian Series, varying between 0.17% in the Cu horizon to 0.47% in the alluvial zone.

CONCLUSIONS

Three significant conclusions emerge from the Egton High Moor experiments. The removal of heather vegetation by muirburn accentuates changes in the surface litter layer, the soil chemistry and the soil fauna. In general however, the profiles remain fundamentally stable. The presence of heather acts as a protective buffer to the soil-vegetation system, with litter accumulating under the Calluna stands. Removal of this protective layer exposes the soil surface to changes, allowing the wind to act as a transporting agent, removing and dispersing the litter layer. Some litter, probably a relatively small proportion, may be

completely lost to the ecosystem, but the exposed soil remains fundamentally stable, with colour, moisture, organic content and textural properties changing little. Variations which do occur can often be related to factors other than vegetation disturbance, for example variations in organic matter may be explained by seasonal variations in floral and faunal activities.

A dominant theme is the crucial importance of the surface organic layer, protecting the soil surface against external change. If the muirburn does not damage this thin protective surface, the soil remains in a state of environmental balance. Should the organic ~~horizon be damaged or destroyed~~, evidence indicates that the delicate buffering system becomes unstable. The cation exchange results suggest that the organic colloids are essential for maintaining the nutrient status of burnt soils and subsequent vegetation regeneration.

Destruction of this organic horizon may result in changes of a catastrophic nature (Radley, 1965; McVean and Lockie, 1969; DoornKamp et al, 1980). Thus, one may distinguish between the effects of controlled burning and wildfire. The moorlands destroyed by the 1976 wildfires on the North York Moors exhibit landscapes of instability and environmental degradation. As an example water samples were taken simultaneously from Bluewath Beck, which drains severely burnt areas of Glaisdale, and Wintergill catchment during a Spring flood of 1979. Sediment concentration at Wintergill was 2.13 mg l^{-1} compared with 602.14 mg l^{-1} in Bluewath Beck. Arnett (1980) found increases in total sediment and organic load by factors of 2 to 3 in Bluewath Beck and increases in drainage density and gully development on Glaisdale following the 1976 fires. While it has been argued that moorland micro-

floral and faunal populations are in a low state of complexity (Cragg, 1961; Latter et al, 1967) the same authors agree that these populations are impoverished by at least one order of magnitude on bare severely burnt moorland.

Changes do occur within the soil following burning, which converts biochemical compounds previously held in a steady-state within the biomass to free salts. The degree of liberation appears to be related to the intensity of the burn. The volatised salts may interact with the processes acting upon them in a number of ways. An important pathway is their translocation into the soil profile, ~~thereby creating a temporary nutrient source held by the organic colloids~~, which may increase soil reaction. However, the change in soil reaction will be multi-dimensional and related to numerous variables.

Muirburn has a marked effect upon soil faunal populations. The removal of heather vegetation exposes the fauna to a number of environmental processes, notably desiccation and freezing. The disturbed environment is detrimental to faunal populations, which are considerably impoverished compared with protected heather moorland environments.

The contrasts between the protective effect of the heather cover and the more erosive burnt moorland environment is further discussed in the two subsequent chapters. Chapter 9 examines relative differences in air temperature, while Chapter 10 compares potential soil erodibility on the two moorland types.

CHAPTER 9

MICROCLIMATIC RESULTS

The design of the temperature monitoring experiment on Egton High Moor has been described earlier. This Chapter is concerned with the differences in recorded air temperature between vegetated and burnt moorland, based on data collected between September 1, 1978 and August 31, 1979. Over the twelve months, 348 days of continuous data were recorded, equivalent to 95.3% of the year. The main loss of record was a 15 day gap between mid-January and early March when severe weather conditions prevented access to the recorder. The data only refer to changes in temperature recorded at two particular points in space. However, temperature varies spatially, as well as through time. Spatial variations in temperature were recorded using thermistors set at different heights, enabling the construction of temperature profiles.

Temperature measurements were taken using a W.P.A. Environmental Multi-Probe with six pre-calibrated thermistors located at heights of 100, 67, 46, 32, 22 and 16 cm above the ground surface (Plate 3b).

A total of 54 profiles were recorded, on the burnt and heather-covered ground. Temperature recordings were taken both above a burnt area of the moderately burnt plot on Egton High Moor and an adjacent heather stand, 32 cm high. Of the 54 profiles, 4 were taken during Winter 1979/80. A total of 30 profiles were taken during overcast conditions on June 14, 1980 and 20 profiles during bright conditions on June 15, 1980. The latter 50 profiles were recorded at 10 minute intervals, with approximately a two-minute delay between recordings on the burnt and heather-covered ground.

All the recordings indicate a general increase of temperature towards ground level (Fig. 35). There is little indication of a distinct difference between the two sets of recordings. T-tests between the two data sets, for each respective height, were not significant.

Warming towards ground level is particularly pronounced on the burnt ground. Mean temperature at 16 cm exceeds mean temperature at 100 cm by 0.26°C on the heather-covered ground and 0.52°C on the burnt ground. The difference is particularly marked on the recordings of June 16, where the mean temperature difference is 0.27 and 0.82°C for the heather-covered and burnt ground, respectively.

The temperature profiles accord with theory on heat flux within the "unstable sub-layer" where temperature is a uniform function of height (Geiger, 1965). Where energy is of the ingoing type, during the day, there is a tendency for a negative exponent between height and temperature. This is reversed during the out-going radiation transfer at night (Oke, 1978).

Several explanations may be offered for the trend. At the heather canopy radiant energy is absorbed and transformed into heat (Stoutjesdijk, 1959). The ability of heather to retain heat results in a general warming within the canopy. The dark colour of the burnt soil allows the absorption of radiant heat, thus warming the surrounding air (Vaartaja, 1949; Viro, 1974). This is confirmed by the low albedo rates recorded for organic soils (Monteith, 1973). Furthermore, both the heather canopy and the roughness of the burnt surface will reduce wind velocity (Oke, 1978). This theme will be discussed in more detail in

Chapter 10. The reduction in wind velocity will diminish heat loss by eddy conductivity (Geiger, 1965; Monteith, 1973).

Having placed the temperature probes within the general spatial context of lapse profiles, attention is now focussed upon the salient differences between the two sets of recordings over an annual cycle. The notation employed in Fig. 35 will be used throughout in the diagrammatic representation of the data, with a solid line representing the heather probe recordings and a dashed line the burnt ground probe recordings.

RESULTS

TIME SCALES OF TEMPERATURE VARIATION

Analysis of the data enables the recognition of three time scales for temperature variation. The shortest involves very rapid changes in temperature over several minutes. Over a longer period one may recognise a diurnal cycle, itself superimposed on a general seasonal variation.

Short-term fluctuations in temperature are frequently recorded, particularly on the open ground, usually induced by warmer periods of direct insolation followed by cooler, cloudy spells. As an example, temperature changes on a particularly variable day, June 14, 1979, are discussed. Over the 12 hour period (0600 to 1800) the heather probe recorded 7 cycles of heating and cooling, totalling 53.4°C of temperature change. The burnt ground probe recorded 14 cycles of heating and cooling, totalling 202.2°C of temperature change. Such rapidity of temperature change accords with observations made by Vaartaja (1949) who found that soil surface temperatures changed by 20°C in a few minutes on Finnish heathlands, due to alternating periods of direct and diffuse

insolation. Similar rapid fluctuations in temperature have been reported over sea surfaces by Lumb (1964).

Such short-term fluctuations are superimposed upon a diurnal cycle with maximum temperatures usually being recorded during early afternoon (1300-1500) and minimum values in the early morning (0300-0500). Barclay-Estrup (1971) has recorded similar diurnal cycles within heather stands in Scotland.

The combination of short-term and diurnal fluctuations produces a complex pattern of change. To illustrate the point, Fig. 36 displays temperature changes recorded by both probes during the week June 11 to June 17, 1979. Both short-term rapid fluctuations and a diurnal cycle may be discerned. During this period total temperature change recorded by the heather probe was 226.5°C , compared with 733.5°C recorded by the burnt ground probe. Delaney (1953) suggests that both heating and cooling are less rapid under heather stands than above exposed ground due to the ability of heather to retain heat and protect the soil from direct insolation. Fig. 36 tends to confirm this assertion, with temperature changes recorded by the burnt ground probe generally preceding those recorded by the heather probe.

Short-term fluctuations and diurnal cycles are superimposed upon an annual cycle, consisting of warming during the Summer months followed by cooling during Winter, with Autumn and Spring being complex transitional periods. The salient characteristics of this annual cycle were investigated using Harmonic Analysis, which attempted to fit a sinusoidal curve to the mean daily temperature values. Significant cycles of temperature change were fitted to both data sets (Fig. 37).

The critical value for significance at the 0.05 confidence level was 5.07, easily surpassed by significance values of 14.11 and 14.44 for the heather and burnt ground data, respectively. Fig. 37 shows the sinuousoidal waves through the annual cycle, with the amplitude of the wave being greater above the burnt ground than the vegetated ground, suggesting greater temperature ranges over the former. The temperature differences between the two data sets over the annual cycle is the main topic of discussion in this chapter.

THE TEMPERATURE DATA

A number of temperature variables have been incorporated into the analysis. For each day of record the maximum, minimum, mean and maximum variation in temperature were calculated together with the number of freeze-thaw cycles and the duration of sub-zero temperatures. This data is summarised in Appendix VII.

The heather probe and burnt ground probe recordings are significantly different as shown in the T-test results in Table 29. For each temperature variable the heather data are significantly different from the burnt ground data. Thus, the different environmental milieux have created two very distinct and different sets of recordings.

Despite the differences between the data sets, both are highly correlated. Part of this inter-correlation may be explained by the fact that some variables are defined in terms of other variables, for instance mean temperature and temperature variation may be defined in terms of maximum and minimum temperature. However, there are significant measures of association between sets of data for each temperature variable (Table 29). A correlation

TABLE 29

T-Test of Temperature Data

Temperature variable	Degrees of Freedom	T-value	Probability	Correlation coefficient between the two data sets	Significance of R
Daily maximum temperature (°C)	347	-8.34	<0.001	0.95	<0.001
Daily minimum temperature (°C)	347	17.13	<0.001	0.92	<0.001
Daily mean temperature (°C)	347	2.12	0.034	0.95	<0.001
Daily maximum temperature variation ¹ (°C)	347	-14.52	<0.001	0.83	<0.001
Daily number of freeze-thaw cycles	347	-4.19	<0.001	0.33	<0.001
Daily duration of sub-zero temperature (hours)	347	-3.74	<0.001	0.92	<0.001

Notes: 1. Daily maximum temperature variation is the result of subtracting daily minimum temperature from daily maximum temperature.

test of all the data revealed 64 significant correlation coefficients between the 12 variables.

To simplify the analysis, discussion is concentrated upon monthly means for each variable, highlighting the basic differences between burnt and vegetated ground and allowing generalisations to be formulated. However, since monthly means are themselves already generalisations, data are highly dispersed around the average values. For example, the coefficients of variation of mean monthly temperature ranged between 14.8 and 795.0%, with mean monthly coefficients for the year of 110.3 and 140.5% for the heather and burnt ground data, respectively.

MEAN TEMPERATURES

A general annual cycle of temperature change may be observed on Fig. 38. Temperatures rise to a peak during the June-August period, falling to a minimum in January and February. Mean temperatures above the vegetated area exceed those on the burnt ground for 8 months of the year and, conversely, are reversed for 4 months. No clear pattern of relative temperature differences emerges, and as mean values obscure many aspects of temperature differences, a more meaningful discussion should concentrate on other parameters.

MAXIMUM TEMPERATURES

Differences may be observed in the maximum temperatures recorded by both probes, and two distinct trends are apparent. Maximum temperatures appear relatively higher over the burnt ground in Summer while in Winter the situation is reversed (Fig. 38). For 8 months of the year mean monthly maximum temperatures are higher on the burnt ground, the difference being particularly marked between

June and September, when the difference is of the order of 2-5°C. A similar pattern is reported by Liddle and Moore (1974) comparing temperatures on grass-covered and exposed sand dunes in North Wales. Lower temperatures within the heather canopy may be partly explained by the effect of the canopy filtering radiation. Gimingham (1964) suggests that less than 20% of incoming insolation penetrates to ground level, while Barclay-Estrup (1971) infers that penetration through mature heather stands may be as low as 2%, which compares favourably with the 1% penetration recorded by Stoutjesdijk (1959) and Van der Poel and Stoutjesdijk (1959) under dense heather stands on the Veluwe of the Netherlands.

On burnt ground, insolation penetrates directly to the ground surface and is converted into radiant heat. Furthermore, the dark soil colour allows heat absorption. As discussed in Chapter 8, the soil surface is characterised by low Munsell Values, partly as a result of charring and partly due to the black colouration of the peat. Such a phenomenon has been reported in a variety of burnt environments. Viro (1974) reports absorption of heat by blackened, burnt forest soils on the Fenno-Scandinavian Shield, while Vaartaga (1949) found that direct penetration of insolation to burnt surfaces produced soil temperatures in the range 50-60°C. According to Lloyd (1968), soil temperatures on sunny days were 1 to 5°C higher on burnt than unburnt rough pastureland in the Peak District.

Both processes, of filtering of insolation and absorption of heat, may explain the recorded temperature differences. Thus, Vaartaga (1949) found maximum soil surface temperature under Callunetum to be 54°C compared with 63°C on burnt soil. The

comparative figures reported by Delaney (1953) are 24.3 and 32.5°C, respectively.

During Winter maximum temperatures tend to be higher above the vegetated ground. The difference may be explained by the heat retentative properties of the heather, accentuated by the effect of the canopy in decreasing wind velocities and subsequent heat loss due to eddy conductivity (Stocker, 1923; Gimingham, 1964).

MINIMUM TEMPERATURES

The processes described partly explain the consistently lower temperatures recorded over the burnt ground. Mean monthly minima may be 3°C lower above the burnt ground than within the canopy (Fig. 38, Tables 30 and 31). As discussed previously the Callunetum canopy retains heat and reduces wind velocity while the open ground is exposed to direct heat loss by radiation and eddy diffusivity.

Freezing cycles are consistently more prevalent above the burnt ground in terms of frequency, duration and intensity. Only two months (June and July) recorded no freezing conditions compared with five months within the canopy (Fig. 39a, Tables 30 and 31). In total, sub-zero temperatures were recorded on 163 days by the burnt ground thermistor compared with 119 days beneath the heather. Freezing was more intense on the exposed ground with the lowest temperature recorded by the heather probe being -8.2°C compared with -8.8°C recorded by the burnt ground probe, both recorded on January 13, 1979. Mean monthly sub-zero temperatures are shown on Fig. 39b. September, October and August record sub-zero mean monthly minima over the burnt ground but not within the canopy. With the exception of November, sub-zero mean monthly

TABLE 30

Summary of data recorded by heather probe

Month	No. of days of record	Mean mean temp. (°C)	Mean maximum temp.	Mean minimum temp.	Mean temp. variability	No. of days freezing recorded	No. of freeze-thaw cycles	No. of hours of freezing	Mean duration of freeze (hrs)	M.M.M. S.Z.T. (1)	No. of days temp. constantly < 0°C
September	30	11.04	14.81	7.23	7.58	0	0	0	0	-	0
October	29	8.43	11.71	5.05	6.66	0	0	0	0	-	0
November	30	4.97	7.38	2.10	5.27	7	4	136.5	4.55	-4.27	2
December	31	0.52	2.40	-1.27	4.49	20	15	302	10.52	-31	7
January	31	-2.37	-1.10	-3.48	2.18	31	7	718	23.16	-3.47	28
February	16	-2.06	-1.34	-2.73	1.54	16	0	384	24.0	-2.73	16
March	28	0.51	2.13	-1.26	3.39	26	17	471	16.82	-1.38	14
April	30	7.67	9.33	1.91	8.96	10	14	110	6.71	-0.99	0
May	31	9.37	16.70	2.17	14.53	9	7	86	2.77	-1.98	0
June	30	14.40	22.07	6.38	15.89	0	0	0	0	-	0
July	31	15.62	23.47	7.75	15.97	0	0	0	0	-	0
August	31	13.37	19.92	7.19	12.74	0	0	0	0	-	0
Total	348					119	64	2207.5			67

(1) M.M.M.S.Z.T. = Mean monthly minimum sub-zero temperatures

TABLE 31

Summary of data recorded by burnt ground probe

Month	No. of days of record	Mean mean temp. (°C)	Mean maximum temp.	Mean minimum temp.	Mean temp. variability	No. of days freezing recorded	No. of freeze-thaw cycles	No. of hours of freezing	Mean duration of freeze (hrs)	M.M.M. S.Z.T. (1)	No. of days temp. constantly < 0°C
September	30	13.25	14.81	7.23	16.08	1	2	4	0.13	-1.00	0
October	29	8.32	11.71	5.05	14.41	7	5	21	0.93	-2.65	0
November	30	3.8	7.38	2.10	8.63	16	9	176	5.87	-3.14	4
December	31	-0.54	2.40	-1.27	14.50	26	12	465.5	15.02	-3.47	11
January	31	-3.12	-1.10	-3.48	1.89	31	3	721	23.26	-3.95	28
February	16	-2.54	-1.34	-2.74	0.32	16	0	408	24.00	-3.60	16
March	28	-0.32	2.13	-1.26	5.19	28	21	479	17.11	-2.68	12
April	30	8.25	9.33	1.91	11.75	24	27	217	8.55	-1.79	1
May	31	7.86	16.70	2.17	18.86	13	20	106	3.09	-3.61	0
June	30	12.61	22.07	6.38	21.86	0	0	0	0	-	0
July	31	16.08	23.47	7.75	20.31	0	0	0	0	-	0
August	31	14.49	19.92	7.19	18.92	1	1	1	0.03	0	0
Total	348					163	100	2598.5			72

(1) M.M.M.S.Z.T. = Mean monthly minimum sub-zero temperatures

minima are always lower on the burnt ground than the heather-covered ground.

The November anomaly is due to mild freezing temperatures being recorded by the burnt ground probe in early November, which were not experienced by the heather probe. During the period November 24 to 30, severe freezing conditions were recorded by both probes. Consequently, the monthly mean sub-zero temperature is lower on the heather probe. However, during late November mean sub-zero temperatures were lower on the burnt ground probe, at -5.5°C , compared with a mean of -4.3°C recorded by the heather probe.

During Winter relatively constant temperatures were recorded by both probes while under a snow cover. The heather probe recorded a constant temperature of -0.9°C , compared with -2.2°C on the burnt ground. Such consistency beneath a snow cover is supported by Thorn (1979) with regard to temperatures in an Alpine environment in the Rocky Mountains and Brown (1976) referring to temperatures in Minnesota peats. Stoutjesdijk (1959) suggests that very cold conditions are associated with clear Winter nights, where snow cover is absent. Hence, there is no insulating layer preventing heat loss by radiation.

The differences in freezing intensity between the two data sets are particularly marked during Spring and Autumn, when temperatures within the canopy are more akin to Summer, while a Winter regime exists on the burnt ground. Consequently, during these transitional seasons the differences are most obvious, a theme discussed later.

The duration of freezing conditions is more prolonged on the burnt ground, where a total of 2598.5 hours of sub-zero temperatures were recorded, equivalent to 108.3 days. The heather probe

recorded 2207.5 hours of sub-zero temperatures, equivalent to 91.9 days (Fig. 40a). Thus, the duration of freezing temperatures within the canopy is 85% of that above the burnt ground. The duration of individual freezes is highly variable. Although the time-resolution precludes precise definition of the duration of short freezes, sub-zero temperatures of less than one hour were often recorded. The longest record of continuous freezing is at least 38 days although the full length cannot be determined due to the data gap.

Fig. 40b shows the mean hourly duration of freezing events for each month. A salient characteristic is the long duration of freezes in deep Winter, particularly January and February, when above-zero temperatures were rare. Under the heather canopy 67 days were recorded during which temperatures never rose above zero, compared with 72 days on the exposed ground.

The prolonged sub-zero events account for most of total freezing duration, as may be observed in the frequency distribution shown in Fig. 41. Under the canopy 50% of all days during which sub-zero temperatures were recorded had a freezing duration greater than 23 hours day⁻¹, compared with 18 hours day⁻¹ on the burnt ground.

Relatively short freezing events, recorded particularly in Autumn and Spring, are of considerable significance for the intensity of freeze-thaw cycling. During the transitional months the duration of freezing is much greater on the exposed ground than under the heather canopy. On the exposed ground short freezes were recorded throughout August, September and October, while none occurred within the canopy.

FREEZE-THAW CYCLES

The number of freeze-thaw cycles is greater over the burnt than over the vegetated ground, although a 15 day data gap prevents a full assessment. Even though the clock mechanism had stopped, variations in temperature were still recorded, ranging from 11.1 to -2.3°C . Thus, freeze-thaw cycles had occurred during this period, but could not be counted. A total of 64 cycles were recorded by the heather probe over the year, 36 less than the burnt ground thermistor. A similar pattern is reported by Chapin et al (1979) comparing freeze-thaw cycles on exposed ground with those within tussocks of Eriophorum vaginatum, on Alaskan tundra.

Freeze-thaw cycles naturally follow a seasonal pattern (Fig. 42). During Winter the cycles are relatively long, while in Spring and Autumn they are shorter, but more frequent. Although the six Spring and Autumn months (March to May and September to November, respectively) represent 50% of the year, they contain 61.8% of the total freeze-thaw cycles recorded within the canopy and 74% above the burnt ground.

TEMPERATURE VARIABILITY

Since both higher and lower temperatures tend to be recorded over the burnt ground, total variability is naturally greater (Fig. 43). This is evident from the short-term variations discussed previously, and also on a seasonal basis, with the mean monthly variability recorded by the burnt ground probe exceeding the heather value for 10 months of the year. Mean monthly temperature variability may be 8°C higher on the former, although for 2 months of the year (January and February) this variability is greater within the canopy. This may be explained by the ability of the canopy to retain heat from periodic warmer spells and diminish wind velocity,

whereas the burnt ground probe is subject to continuous freezing temperatures.

TEMPERATURE AND SEASON

To examine seasonal differences in temperature variables, the year was divided arbitrarily into four seasons, Spring (March-May), Summer (June-August), Autumn (September-November) and Winter (December-February). For each season, means of various temperature variables were calculated (Table 32). The conversion factors (C.F.), for converting heather means into burnt ground means, indicate the magnitude to which the temperature variables are different.

During Spring and Autumn one may observe the greatest relative difference between the two data sets. Within the canopy, temperatures are higher and less extreme than over the burnt ground. In particular, wintry conditions are more prevalent over the exposed ground during the transitional seasons. Perhaps, at a qualitative level, one may suggest that 'Winter' lasts longer on burnt ground than beneath a cover of mature heather.

TEMPERATURE AND ENVIRONMENTAL RESPONSE

The temperature-dependent processes acting upon heather-covered soils appear quite different from those acting upon burnt, exposed ground, and may affect an array of pedological, ecological and geomorphological responses. Temperature is considered to influence a number of soil characteristics, and its effects upon pH, soil fauna and soil structure given further consideration.

i) Temperature and soil reaction

The effects of muirburn on the volatisation of salts held within the biomass has been discussed previously (Chapters 1 and 8). The

TABLE 32

Differences between the two temperature recordings
in selected mean temperature variables

TEMPERATURE VARIABLE	AUTUMN			WINTER			SPRING			SUMMER		
	CONTROL	EXPERIMENTAL	CONVERSION FACTOR (C.F.)	CONTROL	EXP.	C.F.	CONTROL	EXP.	C.F.	CONTROL	EXP.	C.F.
No. freeze-thaw cycles	4	16	4.0	22	15	1.47	38	68	1.78	0	1	-
No. days sub-zero temperatures recorded	7	24	3.40	67	73	1.09	45	65	1.44	0	1	-
Total no. of hours of freezing	136.5	201	1.47	1404	1594.5	1.14	667	802	1.20	0	1	-
Mean duration of freeze (hours)	19.5	8.37	0.42	63.82	106.3	1.67	14.82	12.33	0.83	0	1	-
Mean sub-zero min. temperature (°C)	-1.42	-2.36	1.66	-3.1	-3.67	1.18	-1.15	-2.69	2.34	-	0	-
Mean temperature variability (°C)	6.50	12.97	1.99	2.74	5.57	2.03	8.62	11.93	1.38	14.87	20.36	1.37
Mean maximum temperature (°C)	11.30	13.99	1.24	-0.02	-0.09	4.5	9.39	9.73	1.03	21.82	25.52	1.17
Mean minimum temperature (°C)	4.79	2.66	0.56	-2.49	-3.10	1.25	0.94	-0.68	-0.72	7.11	4.9	0.69
Mean Mean temperature (°C)	8.15	8.45	1.04	-1.29	-2.06	1.60	5.85	5.26	0.89	14.46	14.39	0.99

higher air and soil temperatures experienced by burnt soils may serve as a catalyst in the transformation of salts into a soluble phase. Hence, as soil temperatures rise, the amounts of dissolved salts may also increase, which may, in turn, affect soil reaction. Such a process could partially explain observed increases in soil reaction values consequent upon burning.

Two experiments attempted to examine this hypothesis. Firstly, the solubility of several salts at various temperatures were tested. The second experiment examined soil reaction changes within soil blocks which were maintained at different temperatures.

The salts released by heather burning have been discussed by Allen (1964) (cf Chapters 1 and 8). In the initial experiment 25 g of salt (Analar Grade) was added to 100 ml aliquots of distilled water. For each salt the aliquots were maintained at four discrete temperatures, ranging from 6.4 to 59.1°C. The salt-water amalgams were stirred and stored in their respective conditions for one hour, when the supernatant fluid was decanted, and the salts dried prior to re-weighing.

The solubility results are shown in Fig. 44. A clear relationship is evident between water temperature and the amount of dissolved salts (expressed as a percentage of the original weight) ($r = 0.52$, $P < 0.05$, $N = 15$), although individual ions respond differently in their solubilities. Na_2HPO_4 was the least soluble with $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ at the other extreme. As noted in Chapter 8 only one solution, Na_2HPO_4 , was actually alkaline although all were less acidic than the soils concerned and could contribute to a rise in pH values.

The experiment was extended using heather-covered soil blocks removed from the Egton High Moor site. The vegetation cover was

burnt off in the laboratory and the monolith was subdivided into four, each block measuring 10 x 10 x 10 cm. Soil reaction was measured using samples taken from the top 1 cm and from the whole profile. Each of the blocks was maintained at 4 different temperatures for 5 days. In Chapter 8 soil moisture was demonstrated to be an important variable in explaining soil reaction. Hence, to keep the blocks moist, a total of 4 l of distilled water was sprinkled over the blocks, in 200 ml aliquots twice a day. With the exception of Block 4, the blocks were kept moist. Soil reaction was again measured after 5 days but the results did not display any changing pattern of soil reaction and are inconclusive with regard to the processes described above (Table 33).

To summarise, the burning of heather releases volatised cations which are in salt form and, as indicated in Chapter 8, these are retained by the organic colloids. The higher air temperatures on burnt soils encourage higher soil temperatures thereby increasing the solubility of various salts. Thus, the salts enter into a more soluble phase within the soil to form relatively alkaline solutions which in turn may neutralise organic acids and so encourage higher pH values.

These theoretical reactions were not clearly detected when experimentation more approximated natural conditions. One might suggest that inadequacies in the experimental design, or the influence of external variables prevented their direct observation. However, some theoretical and experimental evidence has been presented which suggests that soil temperature changes induced by vegetation removal may, indirectly, contribute to changes in soil pH.

TABLE 33
Soil reaction at
different air temperatures

VARIABLE	BLOCK 1	BLOCK 2	BLOCK 3	BLOCK 4
Temperature (°C)	4.4	20.3	40.2	80.0
Pre-burn moisture content (%)	57.78	51.35	49.06	50.16
Post-burn moisture content (%)	48.34	51.88	48.72	2.72
Pre-burn pH (all block)	3.12	3.3	3.1	3.4
Pre-burn pH (top 1 cm)	3.25	3.05	3.3	3.3
Post-burn pH (all block)	3.5	3.2	3.2	3.1
Post-burn pH (top 1 cm)	3.3	3.2	3.1	3.2

ii) Temperature and Soil Fauna

The effect of burning upon soil fauna has been discussed in Chapter 8. The sampled micro-arthropod populations on the burnt plot at each sampling time were lower than on the vegetated site. Higher Summer temperatures on the burnt plot will encourage desiccation, which is inimical to soil fauna, particularly Collembola. Furthermore, the greater duration, frequency and intensity of sub-zero temperatures have a similar deliterious effect. The results of such processes has been discussed in terms of the general numbers of micro-arthropods and particular groups, such as Nematoda and Enchytraeidae.

The direct penetration of insolation to burnt moorland is reported to encourage changes in the structure of soil fauna populations (Gimingham, 1960). Invertebrate fauna tend to favour the more open warmer milieu. The invertebrate fauna include spiders (Arachnide : Araneae and Opelionide), Phalangids (Hymenoptera) and ants (Formicoidea). Under the more moist, equable Calluna canopy centipedes (Chilopada) and millepedes (Diplopada) become prevalent.

iii) Temperature and Soil Structure

Temperature differences between vegetated and burnt moorland may have important consequences for soil structure. The tendency for greater freeze-thaw activity in the latter environment will promote soil instability while greater temperature variations will also encourage the development of desiccation cracks.

Theoretically, freeze-thaw cycling is an important geomorphological process and the principal mechanisms involved have been discussed

by James (1974). Soil moisture, held within interstitial spaces, undergoes a phase change upon freezing, accompanied by a volume expansion of approximately 9%. The water forms ice crystals which are of two types, ice lenses or ice needles, the latter known as "pipkrakes".

These crystals heave and support soil crumbs and James (1974) suggests that 4 to 6 degrees of frost may heave particles 10-20 mm in diameter. Matthews (1967) found that a temperature of -12.1°C was accompanied by a heave of 13 mm, according to measurements taken at Malham in North Yorkshire. Upon thawing, the crumb returns to the surface, usually slightly downslope of its original position, thus promoting soil creep. Heaving also leaves the soil surface in a "puffy and friable state" (Soons and Rainer, 1968), highly susceptible to subsequent erosion.

Several workers have reported the erosional consequences of frost-heave. Soons and Rainer (1968) found that marked pebbles moved between 5 and 63.5 cm in two weeks after 11 freeze-thaw cycles in the Southern Alps of New Zealand. Kirkby (1967) reports soil creep rates of $0.010 \text{ cm}^3 \text{ cm}^{-1} \text{ yr}^{-1}$ caused by freeze-thaw cycling on upland slopes in Galloway, Southern Scotland. Harvey (1974) reports that piprake formation was rendering the peat surface of the Howgill Fells more crumbly and friable, supporting Radley's earlier observations in the Peak District (Radley, 1962). The greater number, magnitude and frequency of freezing events on the burnt ground surface suggests that there is a greater likelihood of similar processes being active. Visual observation of the ground surface revealed a number of characteristics associated with frost action. Some 1 to 3 mm under the exposed ground an horizon of pipkrakes were found. These formed during freezing conditions,

but persisted even when surface temperatures rose above zero. The frozen band was approximately 3 cm in thickness, the crystal lengths varied between 0.4 and 1 cm.

Despite the greater freeze-thaw activity within burnt soils, the organic matter appears to play a protective role in impeding the erosive consequences of freeze-thaw cycles. Frost-heave resulted in a general upward heave of the soil by some 1 to 3 cm, often producing cracks in the surface (Plate 13a). The fibrous matter within the O horizon appeared to have a binding effect upon the soil. While pipkrakes did not penetrate the organic layer, they were observed to lift individual soil grains on mineral soil.

Imeson (1970) reports similar observations on exposed mineral soil in Bransdale. Thus, organic matter appears to diminish the potency of soil creep induced by frost-heave and the probability of soil crumb disintegration. In contrast, if burning should destroy the organic horizon and expose the mineral substrate the exposed soil would be highly susceptible to the full erosive effects of freeze-thaw cycles.

Freezing events may also influence rock weathering by nivation. Thorn (1979) suggests that for effective nivation, temperatures of -5°C are necessary, with a sufficient supply of moisture, a concept supported by Latridous (1971) and Fukuda (1972). The heather probe recorded 111 hours of temperatures less than -5°C , compared with 127 hours recorded by the burnt ground, again increasing the likelihood of nivation weathering upon rock surfaces in burnt areas.

The variability of temperature may have much the same effect as freeze-thaw cycling in creating soil instability, through the

formation of desiccation cracks. The rapid fluctuations and variability of temperature of the burnt ground will generate expansive and contractive forces within the topsoil which may encourage cracking (Plate 13b).

Temperature variability may also influence the formation of desiccation cracks indirectly, by affects of temperature on soil moisture. While no overall changes in soil moisture status were detected (cf Chapter 8) rapid wetting and drying, over a short time-span, could lead to the development of desiccation cracks. This has been observed in British uplands by Jones (1971) and Harvey (1974).

The likelihood of cracking through wetting and drying is less on the heather-covered ground than on burnt areas. Apart from the magnitude and rapidity of temperature variation being less on the former, the humidity of the Calluna canopy will impede drying. Delaney (1953) and Leyton (1955) agree that the Callunetum canopy is very effective in retaining and conserving moisture. Gimingham (1964) found that relative humidity under the canopy is frequently higher than 80% and for long periods may attain 95%. Therefore, even if the soil surface beneath the canopy experienced rapid fluctuations in temperature, there is less likelihood of the soil becoming desiccated.

Visual examination of the burnt plots reveal a number of surface cracks in the upper peat surface. The cracks are approximately 5 cm to 10 cm long and 0.1 cm wide. However, one must recognize that even if they were present on the vegetated ground their visibility would be obscured by vegetation.

CONCLUSIONS

Temperature conditions over heather-covered soils and soils where the vegetation has been removed by muirburn are quite different. A heather cover protects the underlying surface from extreme temperatures. Consequently, temperatures above burnt ground are more extreme and variable, with relative differences between the two environmental states being particularly evident during Spring and Autumn. Thus, burnt ground experiences both higher and lower temperatures, and consequently, greater temperature variation, than heather-covered ground. Furthermore, the duration, frequency and intensity of freezes and the number of freeze-thaw cycles are greater on the former.

These differences in temperature regimes promote a variety of environmental changes, only a few of which have been examined here, including soil reaction, soil fauna and soil structure. Higher temperatures experienced on burnt soils may serve as a catalyst in transforming salts to a more soluble phase and so tend to increase soil pH values, and so add a further variable to the complex changes in soil reaction on burnt moorland soils, as discussed in Chapter 8. Theoretical considerations and limited experimental evidence support this hypothesis. The less equable temperature regime on burnt moorland soils may also be deleterious to soil fauna populations and to soil structure, increasing the risk of frost-heave, subsequent soil creep, rock weathering by nivation and desiccation-crack development. However, at a qualitative level soil organic matter appears to diminish the erosive potential of these processes, a subject further considered in Chapter 10.

CHAPTER 10

SNEATON HIGH MOOR RUNOFF PLOT RESULTS

This Chapter is concerned with the analysis of processes, at a more detailed level of investigation, on runoff plots located on Sneaton High Moor. Initial discussion is devoted to vegetation characteristics and preparation of the site to enable the monitoring of soil particle movement. The results of these experiments are discussed and related to spatial and temporal variations in erosivity and erodibility, both on the heather-covered and burnt moorland surfaces.

VEGETATION CHARACTERISTICS

The Callunetum on Sneaton High Moor has been dated at 25 years by the gamekeeper (F. Woodcock, pers. comm.), and parts of the stand are entering the "degenerate" stage (Watt, 1955). The vegetation characteristics were sampled from four 0.5 m^2 quadrats yielding a mean height of 33 cm and an above-ground biomass of 18.4 t ha^{-1} . Both figures are less than the corresponding values for Egton High Moor (38 cm and 29.8 t ha^{-1} , respectively) but are similar to those reported by Mork (1946) and Kayll (1966) (cf Chapter 8).

Large amounts of litter were available on the Sneaton High Moor stand yielding a mean biomass of $91.3 \text{ g } 0.5 \text{ m}^{-2}$ or 3.6 t ha^{-1} compared with 2.7 t ha^{-1} for Egton High Moor. Presumably older heather cover in the former allows a greater accumulation of litter (Cormack and Gimingham, 1964). As discussed previously, heather has a protective effect on the soil surface thereby encouraging accumulation. These descriptions portray the heather cover on Sneaton High Moor as being rather different in character from that

on Egton High Moor. Age may be one differentiating factor, with the older Sneaton cover possessing more properties associated with the 'degenerate' phase in the Calluna growth-cycle. In addition, edaphic conditions are also dissimilar. The Egton soils are classified as sandy, stagnohumic gleys whereas on Sneaton High Moor ironpan stagnopodzols encourage very moist conditions inimical to root development.

THE MUIRBURN

Preparation of the experiment necessitated a muirburn, prior to which the two plots were prepared. Both were on a 6° slope. A 5 by 5 m quadrat was marked off as the burnt plot (Plate 9a), this being at the centre of a larger 20 by 20 m area designated for burning. Locating the plot in the centre of the fire ensured maximum fire intensity. All the fire monitoring procedures described in Chapter 3 were subsequently carried out.

The muirburn itself was undertaken by Forestry Commission staff on November 3, 1978 (Plate 9b). A certain degree of ambivalence exists regarding the intensity of the fire. According to the Fire-Intensity Index, the burn was only moderate (Table 34), but in terms of the temperature changes involved and the amount of fuel consumed, the fire was quite intense. Conditions were not conducive to an intense fire. Kayll (1966) suggests that Autumn burns are often less intense than Spring burns, due to greater amounts of soil moisture present. Certainly, moisture levels were relatively high compared with the Egton Moor situations and vegetation moisture content was also high. Both factors probably contributed to the relatively slow rate of fire advance despite the high mean wind velocity, and as a result, the Index of Fire Intensity was only $1,817 \text{ g cal sec}^{-1} \text{ cm}^{-1}$.

TABLE 34

Results from the fire monitoring on Sneaton High Moor, November 3, 1978

VARIABLE	SNEATON HIGH MOOR	EGTON HIGH MOOR ¹
Wind direction	S/SW	N/NW
Mean wind velocity (m sec ⁻¹)	5.28	3.40
% moisture content of soil (pre-burn)	54.71	39.88
% moisture content of vegetation	48.51	32.19
Mean rate of fire advance (cm sec ⁻¹)	2.50	9.57
Maximum recorded temperature (°C)	400	250
Index of fire intensity (g cal sec ⁻¹ cm ⁻¹)	1,817	10,008
Mean dry-weight of heather and litter (g 0.5 m ⁻²)	462.21	722.31
Fuel consumed (g 0.5 m ⁻²)	366.13	577.32
Fuel consumed as % of total available	85.7	79.62

1. Means of Egton Moor plot results included for comparison.

Temperatures recorded during the muirburn, however, were relatively high. A thermocouple head, located 2 cm above the surface at the edge of the inner quadrat, recorded a maximum temperature of 400°C, considerably higher than that recorded during the Egton muirburns. The higher temperatures may be explained by two factors. Firstly, the amount of wood per mass of shoots increases with age (Gimingham, 1971) and since the stand was relatively old, larger amounts of wood were available for combustion than in the Egton situations. Also the large amounts of litter would encourage higher temperatures adjacent to the soil surface. Altogether, over 85% of the biomass was consumed by the fire. Examination of the soil surface after the fire demonstrated that the muirburn had been "clean", as relatively few shoots remained. The following Spring both the heather and burnt plots were sealed as 20 m² runoff plots, thereby allowing comparative investigations.

SOIL MOVEMENT RESULTS

Preparation of the radio-isotope labelled soils has been described in Chapter 4. Soils used for the shorter experiment were placed in their quadrats on May 15, 1979, while those for the longer experiment were returned to their respective sites on June 6, 1979.

Soil diffusion was assayed on the burnt and heather sites after six and eleven-month exposures. Estimated activity removed during each assay varied in the range 2 to 7% of total remaining activity (Table 35). Soil samples were analysed using the procedures previously described (Chapter 4) and count rates (counts per minute, C.P.M.) were adjusted for background (B.G.) and "quenching". However, as "quenching" often prevented the absolute detection of count rates in excess of B.G., rates in excess of 10 C.P.M. above

B.G. were mapped, using the 'SYMAP' Computer Program. Calibration of the activity represented by 10 C.P.M. indicates that such a count is produced by 18.6 Pico Curies (P Ci), or 18.6×10^{-12} Ci and such low activity represents only a small proportion of remaining activity, at approximately $2 \times 10^{-4}\%$ of activity remaining in the soil (Table 35).

The first set of radio-active soil samples were exposed for 6 months, between May 17 and November 21, 1979, one sample within the vegetated quadrat and the other on the burnt ground. During this period the activity decayed to about 2% of that existing at the time of emplacement (Table 35).

Movement over the 188-day period was assayed by removing 49 samples from each respective quadrat using procedures described in Chapter 4. Estimated activity removed within each quadrat was 463.5 N Ci and 502.1 N Ci (10^{-9} Ci) from the heather and burnt plots, respectively.

The scintillation assay confirmed greater soil movement over the burnt ground. Figs. 45 and 46 display diffusion over the respective plots. On the vegetated ground soil diffused from an original areal extent of 78.5 cm^2 over an estimated 595.1 cm^2 (0.059 m^2). Thus, the soil covered some 7.6 times its original area. On the burnt ground soil diffused over an estimated 1085.7 cm^2 (0.109 m^2), equivalent to some 13.8 times the original area of the soil.

The patterns of movement are complex and do not support the theoretical pattern of preferential downslope movement, suggested by some workers (Kirkby, 1967; Richter and Negandank, 1977; Morgan, 1979). Rather, there is a general movement outward from

TABLE 35

Characteristics of Radio-Active Soil Exposures

	6 MONTH EXPOSURE		11 MONTH EXPOSURE	
	VEGETATED	BURNT	VEGETATED	BURNT
Date exposed	May 17, 1979	May 17, 1979	June 5, 1979	June 5, 1979
Activity when exposed in field (μ Ci)	397.36	397.95	1,882	2,146
No. of days exposed	188	188	344	342
No. of samples removed	49	49	88	94
Activity at end of field exposure (μ Ci)	8.07	8.09	9.72	11.01
Activity at end of exposures as % of activity at beginning	2.032	2.032	0.585	0.453
Exposure as % of year	51.51	51.51	94.24	93.69
Total rainfall (mm)	429.3	429.3	910.5	910.5
% of activity represented by 10 C.P.M. (18.629 P Ci) at end of experiment	2.31×10^{-4}	2.30×10^{-4}	1.69×10^{-4}	1.92×10^{-4}
Estimated area diffusion (m^2)	0.059	0.109	0.406	1.152
Magnitude of order greater than original	7.58	13.83	51.69	146.68
Estimated activity in samples (N Ci)	463.54	502.08	242.54	515.94
Sampled activity as % of estimated remaining activity	5.74	6.21	2.50	4.69

the centre. On the burnt ground there is a tendency for upslope diffusion in a westerly direction, possibly related to wind direction. Overall, soil movement is greater over the burnt quadrat, covering some 1.85 times the area covered within the heather quadrat.

To investigate both spatial and temporal variations in soil diffusion, labelled soils were exposed within the runoff plots for 11 months up to May 1980, on both burnt and vegetated sites. During the 48 hour period between sampling on the respective plots no precipitation was recorded. A total of 182 samples were taken from these plots.

The activity in the soil decayed to about 0.5% of original activity at the time of field emplacement (Table 35). Estimated activity removed was 242.5 and 515.9 N Ci from the heather and burnt plots, respectively. Soil diffusion within the vegetated plot is shown in Fig. 47 where the area covered by radio-active soil was some 0.406 m^2 or 51 times the area of its original distribution.

Although diffusion is multi-directional there appears to be a preferred orientation towards the south south-west and no evidence emerges for preferential movement downslope. Soil movement on the burnt plots follows a somewhat different pattern (Fig. 48). The area covered by the radio-active soil is some 1.152 m^2 , 147 times the area of the original soil distribution, but the trend of soil diffusion is much more complex than on the heather-covered plot. Again, preferential southern distribution is evident, but although this orientation is more pronounced, it is not contiguous with the central source of activity. Next to the central area of activity is a 0.113 m^2 node of active soil, while some 1.65 m to 2.5 m from the centre there is a 0.364 m^2 area of activity. Since the activity is on the edge of the plot, one might infer that the

edging had impeded soil movement.

Preferential downslope movement is evident on the burnt plot. A node of activity is recorded 0.58 m downslope of the original centre of activity, and is not contiguous with the centre. One might suggest that downslope movement on the burnt site may be due to rainsplash or rainwash which will be less effective beneath vegetation.

Temporal trends in soil movement are evident on both sets of plots. The first exposure is equivalent to 51% of the year while the second, of 344 days, represents 92%. The recorded precipitation of 808.7 mm during the longer exposure was some 1.9 times greater than the 429.3 mm collected during the first exposure. However, the areal differences in soil movements between these two periods exceeded the differences in time and precipitation by an order of magnitude.

Over the longer exposure period on the heather plot the area covered by the radio-active soil is nearly 7 times that covered during the shorter exposure, while on the burnt plot the factor exceeds 10. Since other known variables are held constant, one might infer that soil movement is largely operative during Winter. Hence, the area of soil movement on the burnt ground over the longer exposure is 2.84 times that within the vegetated plot.

Radio-active soil cores from the longer exposure were further examined for evidence of vertical diffusion of ^{59}Fe . Samples were counted at successive depths of 1 cm and the results indicate only limited translocation. Of the 35 surface soil samples which yielded significant count rates, only 10 revealed significant counts at depths of 1 to 2 cm. Of these only 1 of the 11 superficial radio-

active samples from the vegetated plot gave a significant count rate. This sample was the central one within the original 10 cm diameter of radio-active soil. Calibration of the count rate indicated that the sample contained 7.1 N Ci, equivalent to 9.1% of the activity in the top 1 cm of the core and 2.9% of activity estimated to be present in the topsoil samples.

Within the burnt plot 9 of the 24 superficial radio-active samples gave a significant count rate. Total activity was estimated to be 11.5 N Ci, or 2.2% of estimated activity within the topsoil samples. All these samples were collected within the central 1 m² of the plot.

The 10 active samples were counted at the 2-3 cm depth. Insufficient sample was available for counting the core from the vegetated plot. Of the 9 samples from the burnt plot, 6 yielded significant count rates. Calibration of activity was equivalent to 1.6 N Ci, or 0.3% of topsoil activity.

Further counting of samples at the 3-4 cm depth revealed that 4 samples gave significant count rates. Activity was estimated at 0.7 N Ci, or 0.1% of topsoil activity.

Only 3 samples were available for counting at the 4-5 cm depth. Activity was estimated at 0.09 N Ci, or 0.07% of topsoil activity.

Other workers have noted high retention of ⁵⁹Fe within the topsoil. Wooldridge (1965) reports 99.5% retention within the uppermost 18 mm, while Coutts et al (1968) report no penetration of activity deeper than 21 mm. In comparison 96.9% of radio-activity within the Sneaton cores is retained within the top 1 cm. However, there is evidence for deeper penetration within the cores than reported

by previous workers but, due to different measuring techniques employed, the results are not directly comparable.

Previous workers have relied upon well-type scintillation counters, which involve no direct contact between the radio-active source and the scintillant. Sensitivity, therefore, is considerably less than that achieved with liquid scintillation instruments. Several of the radio-active soil samples were counted on both the Ekco Autoscaler and SL 4000 scintillation counters. A strong association was computed between the two sets of counts ($r = 0.99$, $P < 0.001$, $N = 13$), taking the form of :-

10(1)

$$\text{C.P.M.} = 101.4 + 56.6 (\text{C.P.S.})$$

where C.P.M. = Counts per minute on the SL 4000

C.P.S. = Counts per second on Ekco Autoscaler

The intercept value of 101.4 suggests that activity at this level will be detected on the SL 4000, but not on the Ekco Autoscaler. Assuming an intercept value of 100, then only 3 samples show any evidence of penetration to a depth of 3 cm and only 1 to 4 cm. No count rate exceeded 10 C.P.M. at the 4-5 cm depth. All these samples were removed from the original 10 cm-diameter disturbed area of radio-activity.

The Ekco Autoscaler is a similar model to those used by Coutts et al (1968) (Isotope Type 653 A and Panax Type 7000). The Sneaton Moor results confirm the Aberdeen results, in terms of limited vertical diffusion of ^{59}Fe . However, the decreased sensitivity of solid scintillation systems reduces the detectability of low amounts of radio-activity deeper within the profile. Thus,

on a more sensitive system, depth of vertical movement appears greater than suggested by previous studies.

One may conclude that ^{59}Fe movement occurred mainly in a horizontal rather than a vertical dimension. Various processes may promote vertical diffusion of ^{59}Fe . These include inwashing of ^{59}Fe labelled fines (Anderson, 1978) and its uptake by the plant root system (Boggie et al, 1958).

Cheluviation, in association with organic acids, subsequent leaching and iron exchange, may be involved (Trudgill, 1977), while faunal activity may also encourage vertical movement of ^{59}Fe within the topsoil (cf Chapters 8 and 9). Counting of shoot and stem samples from above the central area of the vegetated plot did not reveal any upward movement of ^{59}Fe .

RADIO-ACTIVITY IN RUNOFF

In Chapter 4 the ability of labelled soil particles to retain ^{59}Fe was discussed in relation to published laboratory experiments. However, the literature does not provide evidence of ^{59}Fe retention under field conditions. Counting of runoff from exposed field trays was undertaken using solid scintillation counting (Coutts et al, 1968) which, as discussed above, is less sensitive than liquid scintillation counting. Consequently, water samples were removed from the runoff plots on a monthly basis and analysed for radio-active content.

Theoretically, if ^{59}Fe is retained by soil particles and is not leached, then activity should be registered in particulate sediments moved downslope, but not in the runoff itself. Thus, after filtering the sediment in runoff samples, the filters were assayed.

Filtered 2 litre water samples were reduced by evaporation to 10-20 ml to concentrate any ^{59}Fe present. 10 ml samples of concentrated filtered runoff were then counted.

After calibrating the sensitivities, samples were counted both on the Ekco Autoscaler and SL 4000 counters. On the former, the time elapsed for 10,000 counts to be registered was used to calculate count rates, while on the latter, counting proceeded for 10 minutes. On the Ekco Autoscaler 1 N Ci registered a count rate of 4.13 C.P.S. above B.G. The SL 4000 was considerably more sensitive, so that 10 P Ci registered a count rate of 5.37 C.P.M. in excess of B.G.

Due to radio-active decay the proportion of total activity represented by these sensitivity limits declined. On the Ekco Autoscaler 1 N Ci represented $7.51 \times 10^{-5}\%$ of total activity in each respective plot at the first runoff collection period (June 5, 1979), which declined to $6.74 \times 10^{-3}\%$ at the last collection period (April 24, 1980). The corresponding values on the SL 4000 were 8.68×10^{-6} and $9.89 \times 10^{-5}\%$. Thus, the SL 4000 was sensitive to at least one-millionth part of activity present in the radio-active soil samples in each plot.

Despite the high sensitivity to radiation the results proved inconclusive. Only one sample provided any evidence of radio-active content, this being the sediments collected from the heather plot on March 28, 1980, which yielded a count rate of 142.7 C.P.M. on the SL 4000. Adjusting for B.G. and quenching, such a count is equivalent to 1.7 N Ci, representing $9.8 \times 10^{-5}\%$ of activity theoretically remaining in the plot. No activity was detected in the filtered sediments.

Despite the inconclusiveness of these results a number of points merit consideration, since the experiment is the first reported attempt to examine the retentive properties of soils labelled with ^{59}Fe in field conditions. Various problems were encountered in estimating the loss of radio-activity in runoff. Firstly, the results are based on the assumption that all the radio-active soil placed within the plots still remained, although an unknown proportion may have been removed. Furthermore, not all runoff from the plots could be collected. Hence, radio-activity may have been removed in excess runoff.

The results from the scintillation assay suggest that the radio-active soil did not move widely within either runoff plot. Consequently, the radio-active soil did not move to the runoff outlet. Hence, conclusive results were not forthcoming.

Nevertheless, evidence suggests that if radio-activity was being lost, it was doing so at very low concentrations, agreeing with the findings of Coutts et al (1968) who detected no activity in runoff from exposed soil trays. The limited evidence from one significant sample does suggest that the ^{59}Fe was retained within the soil, and not leached into runoff. Thus, while there is little evidence that soil particles retain ^{59}Fe in field exposures, there is no evidence that leaching is effective. These points offer some guidelines for further research into this problem.

EROSIVITY

Soil movement is a function of both the erosivity and erodibility of the environment. Results indicate that movement is related to the presence or absence of vegetation and varies through time.

The individual effects of factors which have influenced soil movement cannot be detected. However, it is possible to consider some of the factors which may have affected the soil movement patterns, including the effect of the erosivity of precipitation, freeze-thaw cycling and wind.

Hudson (1971) defines rainfall erosivity as

"... the potential ability of the rain to cause erosion."

The relationship between rainfall erosivity and soil erosion is complex. Douglas (1976) identifies 14 antecedent and current precipitation variables which are considered to effect soil movement, stressing the importance of rainfall intensity.

Independently, Mazurak and Mosher (1968) and Moeyersons and De Ploey (1976) found a linear relationship between rainfall intensity and splash in laboratory experiments, when the size and velocity of simulated raindrops were controlled. Estimates of critical intensity for splash vary, a value of 10 mm hr^{-1} was suggested as the intensity required to cause soil movement by splash on a Bedfordshire soil (Morgan, 1977), compared with 6 mm hr^{-1} on sloping vineyards of the Moselle Valley, West Germany (Richter and Negandank, 1977).

Rainfall intensity has often been equated with kinetic energy and attempts made to establish relationships between kinetic energy and soil work, by movement, with varying degrees of success (Wischmeier and Smith, 1958; Hudson, 1965; Bolline, 1978). The effect of rainfall duration on soil erosion has also been discussed by Douglas (1976). Pierce (1976) found a rainfall duration of 6 hours necessary for significant splash and slope

wash on bare runoff plots in Ontario.

Precipitation totals were measured monthly on the Sneaton High Moor plots and comparative figures for North York Moors rain gauges are shown in Table 36. Precipitation on the plots accords closely with totals measured at Silpho Moor which lies 8.9 Km to the south-east of the plots.

Total measured precipitation over the year (June 5, 1979 to June 5, 1980) was 829.1 mm, very similar to the long term average for Silpho Moor. However, the presence of the obligatory fencing may have reduced precipitation totals.

The differential operation of the precipitation variables, on both the burnt and vegetated plots, may partly explain the differences in soil movement recorded on the two plots. Vegetation on the heather-covered plot intercepts rainfall and absorbs rainfall energy. Any rainfall reaching the ground surface would be of reduced velocity, since a fall of at least 7 m is necessary for raindrops to acquire 90% of their terminal velocity (Morgan, 1979). Precipitation-dependent processes would act directly upon the burnt soil surface, thus allowing movement by both splash and wash. This is evident in the preferred downslope movement on the burnt plot, which did not occur on the heather plot.

Rainfall erosivity varies throughout the year. Greater rainfall amounts were collected during the longer exposure than the shorter exposure by a factor of 1.88. Evidence from Wintergill suggests that rainfall is more erosive in Winter (Table 11). Although the data do not directly relate to Sneaton High Moor they do suggest that daily rainfall amounts, duration, mean intensity and duration

TABLE 36
Rainfall Totals : North York Moors Gauges

Rain gauges on North York Moors	Rainfall during 1st exposure (mm)	Rainfall during 2nd exposure (mm)	Long term average (mm) (1941-70)
Sneaton Radiation Plots	429.3	829.1	
Randymere Reservoir	466.6	915.8	878
Westerdale	494.7	972.6	930
Silpho Moor	430.3	865.9	881
Farndale Vicarage	484.6	1009.2	910

Total measured precipitation over the year (June 5, 1979 to June 5, 1980) was 829.1 mm, very similar to the long term average for Silpho Moor. However, the presence of the obligatory fencing may have reduced precipitation totals.

of maximum intensity are greater in Winter than Summer. The enhanced erosivity of Winter rainfall may partly explain the greater relative soil movement in that season, on both the heather and burnt plots.

The erosivity of freeze-thaw cycles was discussed in Chapter 9 where the tendency for burnt ground to experience more freeze-thaw cycling than heather-covered ground was noted. Examination of temperature data from the Egton High Moor recorder relating to periods of soil exposure provide further confirmation. During the first exposure (May 17 to November 21, 1979) a total of 20 and 39 freeze-thaw cycles were recorded by the probes above the heather-clad and burnt ground, respectively. The corresponding values for the longer exposure were 101 cycles within the heather canopy and 154 above the burnt ground.

While the Egton data cannot be directly extrapolated to the Sneaton Moor plots, they do provide some evidence for the relative intensity and periodicity of freeze-thaw cycles. Overall, a greater frequency of cycles is recorded above the burnt ground, with a marked seasonal concentration on both vegetated and burnt ground.

The precise effects of freeze-thaw activity upon soil movement within the plots are not clear, although Radley (1962) and Kirkby (1967) suggest that such activity is important generally in upland Britain. Although the precise ^effects of nivational processes on soil movement are not recorded, their potential effect on burnt ground is evident from the temperature data, while both burnt and heather moorland are in a more erosive state during the Winter months.

Wind may also act as an erosive process. The tendency for soil movement in a general northerly direction, particularly on the burnt plot, may be due to the effect of wind. Wind may move particles by creep, suspension and saltation, the last probably being the most effective process (Smalley, 1970; Hudson, 1971).

Movement by saltation may be explained by the Bernoulli effect (Morgan, 1979). For wind to set a particle in motion a critical velocity must be achieved. In laboratory experiments Smalley (1970) reports that a speed of 400 cm sec^{-1} , at 1 m height, was necessary to transport particles with a diameter of 0.25 mm. On the upper half of the moving grain the wind force and direction of rotation are complementary, whereas on the underside the forces act in opposite directions. The differences in pressure create a lifting force which overcomes grain weight, causing it to rise vertically and fall with a trajectory of 6 to 12° . The energy of falling grains is imparted both in a dispersive phase, causing dispersion, and a disruptive phase, inducing soil disintegration.

Saltation is considered to occur in a layer close to the soil surface, with 50% and 90% of the weight of saltating particles moving within 50 and 300 mm of the surface, respectively, (Hudson, 1971). While theory on wind-borne soil movement is well established, attempts to mathematically model the relationship between wind velocity and particle movement have met with varying degrees of success (Skidmore and Woodruff, 1968; Woodruff and Siddoway, 1969; Smalley, 1970).

The effect of a heather cover in reducing surface wind speeds has already been noted (Stocker, 1923; Gimingham, 1964;

Barclay-Estrup, 1971), thereby reducing the competence to transport soil particles. Consequently, wind erosivity is assumed to be greater on bare soil surfaces than on vegetated ones.

To examine this assumption, wind velocity measurements were taken on the Egton High Moor plots using an E.T.A. hot-wire anemometer. Wind velocities were recorded at heights of 100, 41 and 9 cm above a burnt surface and above a surface cover with a 46 cm canopy of heather. In all, 50 velocity profiles were recorded on each site, 30 on June 14, 1980 and 20 on June 15, 1980. Velocities were measured every 10 minutes, over a five hour period on June 14 and a 3.3 hour period on June 15. The time-delay between the two sets of recordings was approximately two minutes.

Although there is a great deal of variation within the data, mean wind velocities, at each height, were greater above the burnt than the vegetated ground (Fig. 49). Mean wind velocity above the burnt ground, at 2.1 m sec^{-1} , was significantly different from the 1.1 m sec^{-1} heather mean, as demonstrated by the T-Statistic ($T = -3.97$, D.F. = 298, Prob. = <0.001). At the 100 cm height the burnt ground mean of 3.4 m sec^{-1} was not significantly different from the heather mean of 2.8 m sec^{-1} ($T = -1.05$, D.F. = 98, Prob. = 0.29). However, at the lower heights, the differences were significant. Thus, mean wind velocity at the 41 cm height was 2.1 and 0.4 m sec^{-1} for the burnt ground and heather mean ($T = -6.15$, D.F. = 98, Prob. = <0.001) compared with 0.9 and 0.2 m sec^{-1} at a height of 9 cm ($T = -4.13$, D.F. = 98, Prob. = <0.001).

The results indicate that heather stands are effective in reducing ground surface wind velocities. Thus, as suggested by the soil

movement maps, wind erosivity is considerably greater on the burnt ground than on heather-covered surfaces.

Wind velocity data recorded by the Sneaton High Moor Didcot Weather Station indicate higher velocities, and therefore erosivities, in Winter. Wind velocity, recorded by an anemometer 2 m above the surface, was entered on to a multi-channel logger every 5 minutes and from these recordings mean daily wind velocities were computed.

Mean daily wind velocity during the total soil exposure period (May 17, 1979 to May 14, 1980) varied between 1.00 and 9.9 m sec⁻¹, with a mean of 3.7 m sec⁻¹ (N = 335). Velocities during the initial exposure were lower, varying between 1.1 and 6.8 m sec⁻¹, with a mean of 3.4 m sec⁻¹ (N = 176). Mean wind velocity during the period when only the longer soil exposure was in the field (November 21, 1979 to May 14, 1980) was somewhat higher at 3.9 m sec⁻¹, varying between 1.0 and 9.9 m sec⁻¹ (N = 173). This tendency for greater wind velocities during the latter phase of the soil exposure period may partly explain the greater relative soil movement on the longer exposure.

SOIL ERODIBILITY

While spatial and temporal patterns of soil movement have been observed, it is necessary to consider the overall erodibility of the moorland soils. According to Morgan (1979, p.21)

"... erodibility defines the resistance of the soil to both detachment and transport."

De Meester and Jungerius (1978) suggest a similar definition, in which soil erodibility is a function of the

"... magnitude of disruptive as opposed to stabilizing forces."

Soil erodibility depends on many factors. In an investigation of 55 United States cornbelt soils, 22 soil and surface properties were necessary to explain 95% of soil loss variance by simulated rainfall (Wischmeier and Mannering, 1969). Luk (1977) suggests that soil erodibility depends on such factors as slope, soil moisture content, bulk density and vegetation cover density. Morgan (1979) also includes aggregate stability, sheer strength, infiltration capacity and organic and chemical content. Bryan (1976) and De Meester and Jungerius (1978) stress the importance of micromorphological features, and include such soil properties as total colloid content, clay mineral character, the abundance of polymers of iron and aluminium hydroxides, organic colloidal material and types of absorbed cations.

Most studies on soil erodibility have measured soil loss in gravimetric terms, referring to the amount of soil moved into collecting devices, both in the field (Morgan, 1978) and in laboratory simulation (Bryan, 1969; Kramer and Meyer, 1969; Luk, 1977). The only reported field exposure of soils labelled with ^{59}Fe was on an eroding 49° slope in Oregon (Wooldridge, 1965). Soil movement was of the order of 2.5 m in eight weeks. Thus, on this comparative basis, soil movement, on both the burnt and vegetated sites, was relatively low.

In a review of 16 indices of soil erodibility, the optimum predictor of erodibility was "percentage Water Stable Aggregates" (Bryan, 1977). Fine-earth soil aggregates, with a particle diameter exceeding 0.5 mm were subjected to a simulated storm of 127 mm hr^{-1}

for 20 minutes. 'Percentage Water Stable Aggregates' (% W.S.A.) was defined as the weight retained on the sieve as a percentage of the original weight. Percentage W.S.A. was found to be the best index of soil erodibility for 88 Peak District soil samples (Bryan, 1969) and 153 soil samples from southern Alberta (Luk, 1977).

Soil samples from the Sneaton High Moor compound were similarly tested for % W.S.A. Each sample was from the top 10 cm, one from the burnt ground and another from the heather-covered ground.

50 g sub-samples of fire-earth fraction aggregates, with particle sizes greater than 0.5 mm, were subjected to an intense simulated storm of 495.9 mm hr^{-1} for 20 minutes. Percentage W.S.A. values were very high (Table 37). Both values were in excess of 80%.

Such values are high when compared with the Peak District soils (% W.S.A. = 49.2 to 67.5), (Bryan, 1969) and the Alberta soils (% W.S.A. = 3.0 to 64.8), (Luk, 1977) indicating that the Sneaton High Moor soils have a relatively low erodibility, despite the increased simulated storm intensity.

Examination of soil texture indicates that the soil is erodible, by both raindrop detachment through splash and wash and wind erosion. Due to the nature of chemical bonds, clay-sized particles are resistant to erosion (Yariv, 1976; Luk, 1976; De Meester and Jungerius, 1978). Thus, clay content is a parameter in the assessment of the Universal Soil Loss Equation (U.S.L.E.) (Wischmeier and Smith, 1965; Wischmeier, 1977).

The colloidal properties of clay are important in resisting erosion (Farmer, 1973). Mazurak and Mosher (1968) report a cation exchange capacity of 0.6 meq/100 g for soil particles with a diameter greater than 530 μm , which increases to 12 meq/100 g

TABLE 37

Characteristics of the Sneaton High Moor Soils

Property	Sample from burnt soil	Sample from vegetated soil	Mean
% coarse fraction (> 2 mm)	6.43	2.70	4.57
% fine fraction (< 2 mm)	93.56	97.75	95.66
% sand (2000-63 μ m)	72.92	60.33	66.63
% coarse sand (2000-600 μ m)	16.65	11.34	13.99
% medium sand (600-212 μ m)	26.41	18.51	22.46
% fine sand (63-212 μ m)	29.86	30.48	30.17
% silt/clay	27.08	39.67	33.38
% silt (2-63 μ m)	22.31	37.42	29.87
% clay (< 2 μ m)	4.77	2.25	3.51
pH	3.2	3.15	3.18
% organic matter (loss-on-ignition)	59.55	55.17	57.36
W.S.A. fine earth ¹ fraction >0.5 mm	90.54	81.80	86.17
W.S.A. fine earth fraction >0.5 mm (after oxidation)	45.31	42.23	43.77
Textural group	Loamy sand	Sandy loam	Sandy loam

1. W.S.A. = % of weight retained after wet sieving at 495.87 mm hr⁻¹.

for particles in the 9.2 μm to 2.3 μm range. They associated the higher CEC values with decreasing particle size and suggested the decrease in soil erodibility with particle size was due to the colloidal properties of the finer particles.

Erodibility increases with particle size in a manner similar to the Hjülstrom curve (Bryan, 1976). Thus, silt and fine-sands are erodible, as suggested in the U.S.L.E. . With increasing particle size erodibility decreases due to the resistance of increasing mass. Using high-speed photography Mazurak and Mosher (1968) found that raindrop impact tended to be absorbed in the large ~~interstitial pores of coarse sands and did not cause detachment.~~ The size at which erodibility is prevented depends partly on storm intensity. In an investigation of Idaho soils, particles with diameters of 3,100 μm were eroded by low-intensity rainfall, which increased to 5000 μm during more intense events (Farmer, 1973). Hence, an overall polynomial relationship between particle size and erodibility is defined (Luk, 1977).

A similar polynomial relationship between particle size and erodibility by wind has been observed in laboratory experiments (Smalley, 1970). Peak susceptibility to wind erosion was associated with particles in the 50 to 500 μm range (Smalley, 1970). Clay particles are resistant to wind and Chepil (1953) reports soil erodibility in wind tunnels to be minimised with a clay content of 35%. In an investigation of Kazakhstan soils the negative association between wind blown soil loss and clay explained 80% of wind erosion variance (Shiyatyy et al, 1972). The same authors found erodibility to increase in the silt-fine sand fractions agreeing broadly with the peak erodibility band of 105 to 210 μm

reported by Mazurak and Mosher (1968) and the 400-500 μ m range reported by Farmer (1973). Both Astbury (1958) and Hutchinson (1980) report the blowing of fine sands within Fenlands. Coarser particles are resistant to wind erosion (Smalley, 1970).

The Sneaton High Moor soils are texturally erodible. The relatively large amounts of material in the silt and fine-sand fractions suggests that the soils are liable to erosion by both wind and water. The burnt sample is 52% by weight in this group, compared with 68% in the heather sample, with a mean of 60% (Table 37). Bryan (1969) suggests a continuum of soil texture erodibility from sandy loam at peak erodibility to clay loam at a minimum. Thus, according to texture, both soils are in the most erodible groups, although their potential erodibility, according to the Water Stable Aggregates experiments, is low.

Organic matter may be an important factor in explaining the relatively low erodibility. Morgan (1979) suggests that soils with less than 2% organic matter content are erodible.

Laboratory simulation of soil erosion has revealed negative correlations between soil loss, by both splash and wash, and organic matter (Wischmeier and Mannering, 1969; Bryan, 1977; Luk, 1977). Field studies of soil erosion have revealed the effectiveness of organic matter in diminishing soil creep (Young, 1960) and the concentration of soil erosion on exposed mineral, as opposed to organic, soil. Such processes have been observed on loess soils in central Belgium (Bolline, 1977) and within a forested catchment in Luxembourg (Imeson, 1977).

Due to the peaty nature of the topsoil, organic content was found to be high, with a mean of 57.4% (Table 37). This compares

with soil organic contents for "non-Histosolic" soils (U.S.D.A. Taxonomy, 1975) varying between 0.9% for Sonoran Desert soils to 10.5% for U.S.S.R. forest soils (Pitty, 1979). The high organic content of the Sneaton soils means that they cannot be given a K value on the U.S.L.E. (Wischmeier and Smith, 1965), in which soil organic matter is a variable.

To examine the influence of soil organic matter, the 'Percentage Water Stable Aggregates' experiment was repeated, after first removing the organic carbon by loss-on-ignition (375°C for 16 hours). The results show a greatly reduced aggregate stability, with mean % W.S.A. only 50.8% of mean organic soil W.S.A. Hence, evidence suggests that organic matter plays an important role in maintaining the low erodibility of the soil. Removal of organic matter greatly enhances erodibility, particularly considering that the textural properties of the soils are such that they are liable to erosion by both wind and water.

Organic matter is generally considered to be important in diminishing soil erodibility, partly through the action of organic colloids upon cation exchange. As discussed above, the cation exchange capacity of soils is considered to influence soil erodibility. However, the low exchange capability of mineral fractions in the Egton High Moor soils suggests that cation exchange capacities are largely a function of organic colloids. Hence, one might hypothesize that the organic colloids are significant in diminishing soil erodibility.

Several workers emphasise the importance of soil moisture in decreasing soil erodibility. Smalley (1970) suggests that moisture renders soil more cohesive, due to the bonding of water

between soil particles. This effect is explained by Yariv (1976) in terms of complex chemical interactions between particles and raindrop water which results in a decrease in the detachment of particles. In laboratory simulations both Chepil (1953) and Shvebs (1968) have demonstrated decreased soil erodibility by splash and wash with soil wetting. Dry soils are also more prone to wind erosion, as discussed by Bryan (1969) and Hudson (1971).

Data collected from the Egton soil plots suggest that moisture content is relatively high, with a mean percentage by weight of 38 (N = 39). Neutron probe readings taken by the Institute of Hydrology on Sneaton High Moor confirmed relatively high moisture levels, varying, at a depth of 10 cm, between 19.6 and 53.5%, with a mean of 46.6% (N = 53) (J. Roberts, pers. comm.). Furthermore, no evidence was found on the Egton plots for a reduction in moisture content due to burning.

The evidence for relatively high soil moisture values within the peaty organic horizon suggests that the soils are in a low state of erodibility. As discussed in Chapter 8, high moisture levels are probably related to soil organic content, as texturally the sand-sized fraction is unable to retain moisture (Brady, 1974; Pitty, 1978). Such a conclusion further emphasises the importance of organic matter in maintaining the low erodibility status of moorland soils.

Numerous workers stress the importance of vegetation cover in explaining soil erodibility. As demonstrated by the soil movement maps, vegetation removal greatly increases soil mobility.

Vegetation may dissipate rainfall energy, thus diminishing the potency of rainsplash and rainwash (Morgan, 1979). According to

Bolline (1978) vegetation

"... reduces, brakes and filters the runoff and in this way reduces its erosive effects."

In laboratory simulations of the runoff process, vegetation proved to be very effective in reducing the amount and speed of surface runoff. Surface mulching at 2 t ha^{-1} reduced runoff velocities from 2.5 cm sec^{-1} , on bare ground, to 0.8 cm sec^{-1} (Kramer and Meyer, 1969). Hence, sediment loss tends to be reduced. In a laboratory simulation of semi-arid slopes the concentration of sediment in runoff was 2.5 times greater on a bare slope than a slope vegetated with young grass stems, when the slope was held at 5° (De Ploey and Savat, 1976). The presence of vegetation also reduces surface sealing and hence prevents a decrease in infiltration rates, as reported for simulated rainstorms on mulched slopes (Lattanzi et al, 1974).

Laboratory simulation of runoff prompted Luk (1977) to suggest an exponential or power function relationship between percentage bare ground and soil erosion, supported by empirical observations from a number of natural conditions, including forests (Elwell and Stocking, 1976), vineyards (Richter and Negendank, 1977) and tropical savannahs (Hudson, 1971).

Runoff samples collected from the outlet of the two plots provide evidence of considerable differences in runoff and sediment losses. In Chapter 6 the various hydrological routes for water within heather moorland were discussed. High interception rates have been observed (Aranda and Coutts, 1967; Barclay-Estrup, 1971) and evapotranspiration from Calluna is a further significant

factor (J. Roberts, pers. comm.). The high moisture content of heather and heather litter has also been noted (Chapters 6 and 8). The removal of heather by burning negates or alters the efficiency of these hydrological transfers and increases runoff volumes. Thus, Arnett (1979) reports runoff volumes on burnt moorland to be 16 times greater than on moorland with a mature heather cover. Runoff collected from the plots suggests that burnt moorland has a greater propensity to generate runoff. A total of 195.18 l of runoff were collected from the plots of which 89.6 l and 105.7 l were collected from the heather and burnt plots, respectively. Due to the considerable volumes of runoff generated during the Winter months by both plots, the volumes collected were limited by the capacity of the collector. Hence, there is no significant difference in the collected volumes ($T = 0.63$, D.F. = 6, Prob. = 0.547).

All the runoff from the first 5 months of the experiment were collected (June 5 to November 6, 1979). During this period 2.138 l of water were collected from the heather plot compared with 9.475 l from the burnt plot (Fig. 50). Hence, runoff on the burnt plot was 4.43 times that on the vegetated plot. The difference was particularly marked between August and November, 1979. Between the collection periods of August 21 and November 6 a total of 0.221 l were collected from the heather plot. In comparison, 6.883 l were collected from the burnt plot, some 31.15 times that collected from the heather plot.

The differences in runoff generation may partly explain the greater amount of soil movement on the burnt ground. Of particular note is the tendency for preferred downslope movement on the burnt plot, which is not evident on the vegetated plot.

Between November 1979 and April 1980 the volumes of water generated by both plots exceeded the capacity of the containers. Consequently, precise differences in runoff are not known. However, the limited data do indicate that runoff volumes are particularly large in Winter, which may partly account for the greater Winter soil movement on both environmental types.

Between November 11 and April 28, 1980, a total of 81.367 l and 96.195 l were collected from the heather and burnt plots, respectively. Thus, in 49.1% of the duration of the experiment, 90.9% and 91.0% of total runoff was generated by the heather and burnt plots, respectively. Due to overflow, this relative amount is probably a gross underestimate. However, the data do allow some observations on the periodicity of runoff, in that runoff in "Winter" is far greater than in "Summer". Consequently, soil particle movement is considerably enhanced during this more erosive Winter period on both moorland types, as suggested by the soil movement maps.

The runoff volumes are not directly proportional to precipitation amounts. There is a tendency for greater evacuation of precipitation as runoff during Winter. During the first period (June 5 to November 6, 1979) a total of 353.4 mm of rainfall was collected by the rain gauge. Hence, 40.5% of precipitation collected during the experiment generated only 9.1% and 8.9% of total runoff on the heather and burnt plots, respectively. Some 60% of total rainfall generated over 90% of recorded runoff on both plots. The 11.0 mm of rainfall collected between April 28 and May 12, 1980 did not generate any runoff.

A variety of reasons may be suggested to explain the greater

runoff volumes relative to rainfall during Winter. Generally, the efficiency of hydrological processes which diminish runoff are reduced in Winter. The lower temperatures, as demonstrated by the autographic recorder (Chapter 9) reduce potential evaporation (Ward, 1975), while evapotranspiration losses from Calluna fall to about 0.1 mm day^{-1} (J. Roberts, pers. comm.). Ground freezing impedes infiltration leading to greater runoff, while visual observations of snowmelt demonstrate that snowmelt accelerates the release of water from the plots.

Such a Summer/Winter dichotomy in runoff generation accords with the data from Wintergill. During the Summer months ~~29.2% of~~ precipitation entering the catchment was estimated as leaving in runoff, compared with 57.3% in Winter.

Sediment loss is also mainly associated with high Winter runoff (Fig. 50). In all 4.2 g of sediment were collected from the heather plot, compared with 5.53 g from the burnt plot. Again, the data require some caution due to Winter overflow. Hence, there is no significant difference in the volume weighted sediment loss between either plot ($T = 0.27$, D.F. = 6, Prob. = 0.798).

During the first five months of the experiment 0.3 g of sediment were collected from the heather plot, compared with 1.4 g from the burnt area. Thus, during the period when runoff data are considered accurate, sediment loss from the burnt plot is 4.32 times that from the heather plot. This is a considerably lower proportion than the 20 fold difference reported by Arnett (1979). Visual examination of the sediments revealed that they were mainly composed of heather litter and particles of peat.

Winter sediment loss is much greater. During the period November 11, 1979 and April 28, 1980, a total of 3.9 g of sediment were collected from the heather plot, and 4.1 g from the burnt plot. Hence, 49.1% of the duration of the experiment, 95% and 75% of sediment loss was recorded from the heather and burnt plot, respectively. Again, the proportions are probably an underestimate, due to overflow.

Sediment loss from both plots is mainly concentrated in Winter, suggesting that both burnt and vegetated moorland enter a more erosive state during this period. Verification of such a state is evident from the temperature data (Chapter 9) and from the measured sediment discharges from Wintergill catchment (Chapter 7). Thus, the enhanced erodibility of both burnt and heather moorland is demonstrated by comparison of the 6 month and 11 month soil exposures.

As discussed above, the removal of vegetation by burning exposes the soil surface to erosive processes. Evidence of the change is forthcoming from the runoff data, with burnt moorland generating relatively greater amounts of runoff. The altered hydrological system of burnt moorland, plus the removal of the protective properties of the heather canopy, encourage greater soil movement and sediment loss.

CONCLUSIONS

In this Chapter the scale of enquiry was reduced to examine environmental processes within small plots. The exposure of four sets of isotope-labelled soils has facilitated observations on spatial patterns of soil movement and their temporal variations. The assays of soil movement revealed greater movement

on the burnt ground, both after 6 and 11 month exposures, by factors of 1.9 and 2.8. Comparison of the two respective exposures indicates that soil movement is particularly marked in Winter. Examination of soil cores from the plots demonstrated only a limited amount of vertical diffusion within the profile, with over 96% of measured activity occurring in the top 1 cm.

Runoff samples revealed little radio-activity despite the high sensitivity of the counting apparatus. Only one sample, of sediments collected from the heather plot, gave a significant count rate, indicating that if ^{59}Fe is being lost, it is doing so in low concentrations.

The patterns of soil movement were related to both the erosivity of the environment and soil erodibility. The removal of vegetation by burning alters the relative effectiveness of several environmental variables, in particular, rain erosivity, freeze-thaw cycling and wind erosivity. The burnt soil surface was more susceptible to these erosive processes, inducing greater soil movement. The soil movement maps present evidence of soil movement by wind and rainwash/rainsplash. Comparison of the maps at different points in time suggest that erosivity is greater on both heather and burnt moorland in Winter.

Examination of soil properties suggests that the soil has a low erodibility. Comparison with the only other reported field exposure of ^{59}Fe labelled soil revealed relatively little movement. Soil textural properties suggest a high erodibility, by both wind and water, although organic matter appears to act in the opposite direction, as suggested by the Water Stable Aggregates experiment. Organic matter is important in maintaining a high

moisture status and the cohesive properties of the soil colloidal fraction, further reducing erodibility. Again, the crucial protective role of organic matter is a recurring theme.

The differences in soil movement between the heather and burnt moorland plots is attributed to the effects of vegetation.

Burning of the heather removes the protective effect of the canopy and alters the efficiency of various hydrological transfers.

Consequently, sediment and water losses from the burnt area are greater than their heather equivalents. Further evidence for the greater erosivity in Winter is forthcoming from the seasonal distribution of water and sediment loss.

CHAPTER 11

SYNTHESIS AND CONCLUSIONS

"All aspects of the Moors would have to be considered - the flora, fauna, geology and even the works of man, which forms an impressive whole, one part influencing the other in countless ways and degrees."

F. Elgee, 1914.

In this chapter the results of the investigations, at the three scales of enquiry, are compared and integrated. Such collation allows discussion on the different processes operative within heather moorland, in both disturbed and undisturbed states, and the chapter concludes with a commentary on the contribution to existing knowledge made by the current project, with recommendations for further study.

The first general conclusion is that mature heather moorland, with an undisturbed soil surface, is a hydrological and geomorphological system in a low state of erodibility. Despite a cool, humid, upland environment, vegetation protects the soil surface from processes acting upon it, allowing little release of matter from the system, either as water or sediment.

At the largest scale of enquiry, the catchment as a whole, this protective effect is evident in the hydrological budget.

Relationships between hydrometeorological variables are complex and affected by numerous factors, thus the association between daily precipitation and mean daily discharge is low, with a correlation coefficient of $r = 0.23$ ($N = 187$). The net effect of various hydrological storages and transfers within the system

is such that a relatively small volume of water, estimated at 38% of the annual total, is released from the system. Proportionally, water yield from Wintergill compares more closely with lowland catchments. At a smaller scale, the runoff plots, further evidence is found for the conserving effect of heather vegetation, and this theme is discussed when comparing processes on burnt and vegetated moorland.

Sediment release from mature heather moorland is very low. The heather stands, besides reducing the amount of potentially erosive runoff, impede the movement and release of sediment. This is clear from the pebble study, where low orders of movement were recorded over an annual cycle. The pebbles, with a mean weight of 10.1 g, moved a mean distance of 13.4 cm (N = 85). Computation of sediment yields from the catchment demonstrates that sediment release, in various forms, is relatively low.

An estimated suspended sediment output of 1.51 t/Km²/yr, is the third lowest reported for instrumented catchments in the British Isles, the lowest also being a heather moorland basin in Somerset (Finlayson, 1977). The Wintergill value accords more closely with that for a lowland catchment, the 1.2 t/Km²/yr reported for Drewton Beck, East Yorkshire, by Imeson (1971). Again, a heather moorland catchment, in an upland erosive environment, is functioning in a manner similar to lowland catchments, in a low state of erodibility.

Contemporary erosion is primarily in a solutional phase with solutes forming over 96% of the total suspended sediment budget. Again, on a relative basis, estimated solute losses are low, at 23.4 t/Km²/yr, being the second lowest recorded in the British

Isles, with only the East Twin Brook value, at 16.5 t/Km²/yr recording lower losses (Finlayson, 1977). This low release of solutes is further emphasised by the relatively low losses of dissolved organic matter estimated at 0.38 t/Km²/yr, which compares with losses ranging between 1.7 and 4.7 t/Km²/yr reported for larger North York Moors catchments by Arnett (1977).

Computation of total suspended sediment losses, at 24.9 t/Km²/yr, ranks Wintergill's denudation rate as the second lowest reported in the British Isles. As noted previously the lowest is also a heather catchment, with a denudation rate of 16.8 t/Km²/yr, further emphasising the protective effect of Calluna in diminishing the erodibility of the underlying soil.

While the low erosion rate of mature heather moorland is documented, one might even suggest that it is in a state of accretion, with a net increase in the mineral/organic complex. External sediment may enter via atmospheric sources and, although the results are tentative, estimated sediment inputs exceed suspended outputs by a factor of 3.2, the corresponding values for solutes being 2.8. The catchment itself, in generating litter, supplies material for possible removal. Estimated mean litter accumulation within the heather plot of 0.021 cm (N = 14) compares closely with the mean accumulation of 0.025 cm reported elsewhere (Imeson, 1971). The relatively high proportion of particulate organic sediments discharged from Wintergill, at a mean 35.9% of total particulate suspended sediments (N = 73), further reduces the loss of mineral components. Estimated inputs, as heather litter, exceed estimated outputs by a factor of 4.1. Furthermore, an undefined proportion of organic sediment output, in both

particulate and solutional phases, is autochthonous and thus do not represent a loss from contributory source areas, thereby further reducing actual sediment losses. Such evidence suggests that mature heather moorland is undergoing little erosion and may be experiencing sediment accretion. This protective effect is further clarified if one compares processes on moorland which has undergone controlled burning, with those operating in mature heather environments.

Removal of heather by burning creates a disturbance to the moorland system but the changes induced are complex. In general, the lack of a protective cover allows the system to enter a more erodible state.

Removal of the vegetation cover increases the frequency and amplitude of air temperature variation, as indicated by the Egton High Moor data. Temperatures over random, diurnal and annual cycles are more variable on the burnt ground. Thus, over one week the total variation recorded by the burnt ground probe exceeded the equivalent heather value by 437°C . The periodicity and duration of freezing events is enhanced by vegetation removal, with the burnt ground probe recording freezing temperatures in three more months than the heather probe. Furthermore, the number of freeze-thaw cycles, number of days on which freezes were recorded and the hourly duration of sub-zero temperatures on the former exceeded that recorded by the heather probe by 36, 44 and 323, respectively. Such a contrast further re-emphasises the protective effects of mature heather stands. The temperature changes induced by vegetation removal are also considered to affect soil reaction, soil fauna and soil structure.

Burning of the heather cover creates a disturbance to geomorphological and hydrological operations, such that the burnt soil surface is more liable to erosion by wind and water. Runoff volumes are greater on burnt than vegetated ground. During the 5 months when data are considered most accurate, runoff volumes from the burnt plot on Sneaton High Moor exceeded those on the heather plot by a factor of 4.4. This enhanced runoff encouraged greater sediment losses during the corresponding period by a factor of 4.3.

The erosivity of wind is enhanced on burnt moorland, as demonstrated by the wind profile data, with a mean velocity of 1.14 m sec^{-1} recorded within and above the canopy being significantly different from the 2.09 m sec^{-1} recorded above the burnt ground ($N = 150$). The changes in micro-relief were observed in the mean lowering of $0.33 \text{ (} N = 15 \text{)}$ and $0.39 \text{ cm (} N = 16 \text{)}$ on the moderately and intensively burnt plots, respectively. Further evidence of enhanced wind erosivity is found in suggestions of greater wind-induced soil movement on the burnt Sneaton High Moor plots. In contrast, a tendency for litter accumulation was recorded beneath the heather plot. However, the evidence suggests that loss and accumulation of material may occur on both moorland types, with a tendency for accumulation under heather stands and loss on burnt ground.

The effect of enhanced rain and wind erosivity is revealed in the soil movement results. Movement of radio-isotope-labelled soils provides evidence of much greater soil movement on the burnt ground, in terms of areal diffusion by factors of 1.85 and 2.84 over five and eleven-month exposures, respectively. This again provides further evidence of the protective effect of the heather canopy.

While observing the basic distinction between the protective effect of mature heather and the more erodible burnt surface, processes do not operate at a constant rate throughout the annual cycle. Results indicate that erosion is much more active during Winter, in both environments.

At the catchment scale such enhanced erosivity may be observed in the differences in the nature of 'Winter' as opposed to 'Summer' rainfall. Enhanced erosivity, plus the reduced efficiency of several hydrological transfers, encourage greater evacuation of rainfall as runoff. Hence, an estimated 29.2% of precipitation was evacuated as runoff in Summer, compared with 57.3% in Winter. While statistical associations occur in Winter between precipitation variables and stream discharge, none were found between in Summer, suggesting a diminished responsiveness in the latter. The greater evacuation and runoff from the catchment in Winter resulted in greater sediment losses during this period. An estimated 68% of annual suspended sediment was lost during Winter, the respective percentages for solutes, dissolved organics and bedload being 65, 58 and 75%.

At the micro-scale, basic Summer and Winter contrasts also emerge. While differences between the heather and burnt moorland temperature data have already been noted, both environments experience a potentially more erosive regime in Winter. The direct effects of such a seasonal concentration of erosive processes is evident in the soil movement maps. While the contrast between burnt and vegetated ground has already received comment, temporal variations in soil movement were also observed. Contrasts between the six and eleven-month exposures highlights the difference,

with areal diffusion of the second exposure exceeding that of the first by factors of 6.9 and 10.6 on the heather and burnt plots, respectively.

Moorland disturbed by controlled burning does not appear to undergo automatic catastrophic degradation, although evidence would suggest that burnt moorland is potentially more erodible than its vegetated counterpart. The burnt environment appears to possess a buffering capability, and available evidence would suggest that the organic component is crucial in this respect.

Results from the Egton High Moor soil plot study indicate that the observed soil properties are fundamentally stable. Thus, colour, moisture, organic matter and textural properties are little changed, and those alterations which do occur can often be related to variables other than burning. Changes in soil organic matter may be associated with seasonal variations in biogenic productivity, while variations in soil reaction may be related to the burning process, soil moisture levels, clay content and organic content, with a multiple regression coefficient of $r = 0.56$ ($N = 39$) between soil pH and the latter three variables. However, the faunal data do suggest that burnt moorland is more inimical to soil micro-arthropod populations, especially in Winter. The total micro-arthropod population (in numbers per m^2) on the burnt plot is equivalent to only 68% of the heather plot population in July. In January the equivalent value had fallen to 55%.

The stability of the various soil properties appears to be related to the maintenance of a superficial organic layer, the loss of which would initiate a complex series of processes encouraging

degradation. In particular, loss of organic matter results in rapid soil moisture loss, due to the sandy texture of the mineral fraction. Qualitatively, soil organic matter was observed to impede the full erosive potential of freeze-thaw cycling, and the development of desiccation cracks.

Ion-exchange measurements indicate that cation exchange is mainly a function of organic matter, with fine-earth fractions possessing a mean CEC of 45.9 meq/100 g (N = 4), which was reduced to 4.7 meq/100 g (N = 4) after oxidation. Thus, destruction of the organic layer accelerates the translocation and loss of nutrients volatilised by burning, thereby reducing the nutrient base for regenerating vegetation. Some evidence of the effects of organic matter in diminishing soil erodibility is forthcoming from the Water Stable Aggregates experiments, where removal of the organic component reduced aggregate stability by 49.2%. The evidence suggests that the thin organic layer of burnt moorland soils performs a crucial role by protecting and buffering the soil against external change. Destruction or damage of this layer may initiate a series of processes resulting in erosion of a catastrophic nature, such as occurred due to the accidental fires on Glaisdale in the dry summer of 1976 (Doornkamp et al, 1980). Hence, land management regimes must be designed to ensure that the fires do not destroy the organic matter within the soil.

On a qualitative level the contrast between controlled and accidental burning may be observed within the North York Moors. On controlled muirburn sites, regeneration of pioneer heather stands is evident only one year following the burn. Thus, while the system may degenerate in the long-term, over the short-term it

appears capable of regeneration and return to the low-erosion state of mature heather moorland. The areas burnt by wildfire in 1976 exhibit less evidence of regeneration where rapid destruction and erosion of the environment are evident. Thus, one may suggest that intense moorland burning has destroyed most of the protective organic layer. Removing the heather cover from moorland soils changes the environmental system from a low or negative erosive state to a more degradational one. However, the degree of increased erosion is not as damaging, in the short-term, as that experienced by severely burnt moorland.

This dissertation is a contribution to knowledge concerning environmental processes within heather moorland. A number of contributions may be identified, both of a technical nature and concerning particular process/response relationships.

The soil diffusion study may be considered as a more refined method for monitoring soil movement. The experiments undertaken are the first reported exposures of soils labelled with ^{59}Fe in field conditions within Europe. The experiments also attempted to include some of the more recently developed techniques in radiation detection, not incorporated in previous studies (Wooldridge, 1965; Coutts et al, 1968). While the technique has considerable potential, it also presents problems. The necessity for using relatively low amounts of radio-activity and the need for rapid decay presents a problem of radiation detection at the end of the experiment, when residual radio-activity is very low. Hence, the sensitivity of detection equipment imposes limits upon detection. While liquid scintillation detectors are highly sensitive, the problem of quenching introduces variations

in count rate not due to radiation. To some extent, this may be overcome using a quench curve, but this itself introduces ambiguity with regard to counts of very low amounts of radio-activity, such as Pico-Curies (10^{-12} Ci).

While absolute detection of radio-activity poses problems, the technique offers potential for field studies. Potential is particularly promising for studies of relative soil movement under controlled environments, rather than studies of absolute rates.

The field data do clarify several ideas on environmental processes within heather moorland. The catchment study provides information on the amounts and types of sediments released from a small basin. Most studies concentrate on sediment and solute losses from catchments, ignoring the bedload and organic components. The Wintergill study suggests that, at such a scale, the removal of both components is of considerable significance. Taking the soil plot and catchment data together suggests that mature heather moorland is an accreting system, and as such agrees with similar notions suggested by Finlayson (1977) with regard to upland Somerset and Imeson (1971) with respect to the North York Moors. Comparison of processes on burnt and vegetated moorland permits a more exact assessment of the relative efficiency of particular processes. While such processes have often been alluded to, field data have been generally lacking. Hence, the Egton temperature data clarify some of the recordings on relative temperature conditions on both heather-clad and burnt moorland described by Delaney (1953) and Barclay-Estrup (1971). However, the Egton data analysis appears to be the first based upon continuous monitoring over an annual cycle.

While evidence has been presented on changes in erosion consequent upon moorland burning (Imeson, 1971) an investigation on actual soil diffusion on both burnt and heather-clad moorland has not been previously undertaken. Thus, the soil diffusion experiments have allowed some contribution to knowledge on relative potential erodibility on both burnt and vegetated moorland.

DIRECTIONS FOR FURTHER RESEARCH

Several themes merit further investigation, a number of which are currently receiving attention. Three grey areas stand out, concerning the movement of water, sediments and nutrients through the moorland environment.

Several problems remain concerning the movement of water through the mature heather moorland environment, some of which are being investigated. The Institute of Hydrology has established an automatic weather station on Sneaton High Moor, collecting hydrometeorological data within the mature heather environment. Further work is in progress monitoring the movement of water through Wintergill catchment, with the use of neutron probes, throughflow troughs and piezometers (C. Dunn, pers. comm.).

The development of a data base on processes within heather moorland should allow the Wintergill project to proceed to a further stage. Burning of the catchment will allow observations on the changes induced by vegetation removal and particular attention should be directed towards hydrological transfers and the amounts and types of sediment released from the catchment. Continuation of the monitoring procedures could facilitate knowledge on the affect of catchment recolonisation on these various processes.

Further attention is required concerning the differences in environmental processes on areas which have experienced wildfire and controlled burning. As discussed qualitatively, the Moors which have experienced wildfire are subject to far greater erosion than moorlands which have undergone controlled burning. Erosion on devastated areas of Glaisdale is currently receiving attention (M. Bridges, E. Maltby, pers. comm.) and comparison of mildly and severely burnt moorland should clarify the importance of soil organic matter in buffering the moorland environment against erosive processes.

The investigation of physical processes on moorland, in various stages of heather-growth, and burnt heather moorland, both controlled and accidentally burnt, should be incorporated with studies on nutrient cycling within the moorland environment. As discussed in the literature review, information on nutrient cycling within moorland is sparse. Some data are available on inputs and outputs of nutrients to the system (Elliot, 1957; Allen, 1964; Chapman, 1967) but little is known concerning the pathways of nutrients within the moorland environment, on burnt and mature heather moorland. Hence, further investigations of nutrient cycling should attempt to break into this "black box" and produce more information on the dynamics of nutrient transfers within the moorland ecosystem. This theme is currently receiving attention, both on a large scale, within the North York Moors, and on a small scale, within Wintergill catchment (R. Aspinall, pers. comm.).

The analysis, collation and synthesis of these various research programmes should have practical benefits for land management and conservation within the moorland environment. Hopefully, such

work should contribute to moorland management based upon scientific and ecological principles.

APPENDIX I

SOIL SAMPLING PROGRAMME FOR THE
EGTON MOORS SOIL PLOT STUDY

SAMPLE 1: Pre-burn samples

Soil samples were extracted from the control plot on 14/3/78 and from the moderately burnt and intensively burnt plot on the 16/3/78.

10 cm cores were taken from the following co-ordinates

A1	F1	K1	P1	U1
A6	F6	K6	P6	U6
A11	F11	K11	P11	U11
A16	F16	K16	P16	U16
A21	F21	K21	P21	U21

SAMPLE 2: Post-burn samples 1

Soil cores were taken from the moderately burnt plot on 7/4/78 and from the intensively burnt plot on 24/4/78 following the respective muirburns from the following co-ordinates.

B2	G2	L2	Q2
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SAMPLE 3: Post-burn samples 2

Soil cores were taken from the three plots on 18/10/78 from the following co-ordinates

C3	H3	M3	R3
C8	H8	M8	R8
C13	H13	M13	R13
C18	H18	M18	R18

SAMPLE 4: Post-burn samples 3

Soil cores were taken from the three plots on 24/4/78 from the following co-ordinates

D4	I4	N4	S4
D9	I9	N9	S9
D14	I14	N14	S14
D19	I19	N19	S19

EROSION PIN SURVEY

Erosion pins were inserted into the moderately burnt plot and control plot on 7/4/78 and into the intensively burnt plot on the 24/4/78, in the following co-ordinates

E2	J2	O2	T2
E7	J7	O7	T7
E12	J12	O12	T12
E17	J17	O17	T17

The erosion pins were resurveyed on the 24/4/79.

APPENDIX II

DETERMINATION OF TOTAL ORGANIC CONTENT
IN STREAMWATER

Reagents

- i) Standard potassium dichromate (0.05 N).

Dissolve 2.452 g of dry reagent grade $K_2Cr_2O_7$ in distilled water and make up to 1 litre.

- ii) Ferrous sulphate (0.03 N).

Dissolve 8.4 g $Fe SO_4 \cdot 7H_2O$ in distilled water. Add 20 ml conc. H_2SO_4 , cool and dilute to 1 l. Filter solution and store in stoppered brown glass bottle.

- iii) Sulphuric acid and silver sulphate.

Dissolve 12 g of Ag_2SO_4 in each litre of conc. H_2SO_4 .

- iv) Phosphoric acid (Ortho - 85%).

- v) Barium diphenylamine sulphonate (Indicator).

Prepare a 0.3% solution by dissolving 0.15 g in 50 ml of warm distilled water.

Glassware

N.B. All glassware should be thoroughly cleaned to prevent contamination by organic matter.

- i) 250 ml wide mouthed Erlenmeyer flasks with glass and polythene stoppers.

- ii) Volumetric ware: 5 ml transfer pipette
 10 ml micro-burette
 50 & 100 ml transfer pipettes
 10 ml graduated cylinder

Sample pre-treatment

Particulate matter

- i) Filter a known volume of stream water through a Whatman GF/C filter in 'Millepore' filtration apparatus.
- ii) Dry the filter paper for 30 mins. at 80°C and cool in a desiccator. Place filter in Erlenmeyer flask.

Dissolved matter

- i) Measure a 250 ml sample and store in flask.

Procedure

One reagent blank to accompany each series of tests either

- 1) A blank Whatman GF/C filter.
- 2) A 250 ml aliquot of distilled water.

- i) Pipette 5 ml standard dichromate into the flask. Swirl gently to disperse sample in dichromate.
- ii) Measure 11 ml conc. H_2SO_4 into a graduated cylinder (1 ml excess is allowed for the acid adhering to the sides of the cylinder). Add rapidly to flask and swirl gently. Swirling should continue for 30 secs.
- iii) Stopper the flask lightly with glass or polythene and immerse in boiling water bath so that neck of vessel is cooled by ambient air (N.B. mixture should not be boiled directly).
- iv) Maintain flask in bath for 3 hours. Upon removal hold flask at steep angle and rotate to rinse lower part of neck with oxidising mixture.
- v) Cool to room temperature and (in the case of the particulate tests) dilute with 100 ml of distilled water.

- vi) Add 10 ml orthophosphoric acid and 2/3 drops of indicator. Titrate with ferrous solution. End point sharp and reversible (purple to bright green).
- vii) Standardise the ferrous sulphate. Pipette 2 x 5 ml sample of 0.05 N dichromate into clean titrating flasks. Add 150 ml distilled water and 5 ml H_2SO_4 to each and then allow to cool. Add 10 ml orthophosphoric acid and 2 drops of indicator. Titrate as in (vi). Ferrous sulphate solution should be standardised weekly.

CALCULATIONS

- i) Standardisation of reductant.

$$\text{Normality Fe}^{++} = \text{ml} \frac{\text{dichromate} \times \text{Normality dichromate}}{\text{ml Fe}^{++} \text{ solution}}$$

- ii) Oxygen consumed (O.C.).

$$\text{O.C.} = (\text{Reagent blank titre} - \text{sample titre (ml)}) \times \text{Normality Fe}^{++} \times 8.$$

Value is mg O_2 required by the sample.

- iii) Total organic matter (T.O.M.).

Convert to take into account oxygen equivalent.

$$\text{T.O.M. (Mg)} = \text{O.C.} \times 0.699.$$

Convert into Mg l^{-1}

- iv) Total organic carbon (T.O.C.).

$$\text{T.O.C. (Mg)} = \text{T.O.M.} \times 0.35.$$

Express concentrations as in (iii).

APPENDIX III

DETERMINATION OF SOIL ORGANIC MATTER CONTENT

Reagents

- i) Potassium dichromate N solution.
Dissolve 49.035 g of $K_2Cr_2O_7$ in distilled water and make up to 1 l.
- ii) Ferrous sulphate 0.5 N.
Dissolve 140 g of ferrous sulphate in 0.5 N sulphuric acid to make 1 l of solution.
- iii) Conc. sulphuric acid.
This shall have a specific gravity of 1.84.
- (iv) Phosphoric acid (Ortho - 85%).
- (v) Barium diphenylamine sulphonate (Indicator).

Glassware

- i) Glass weighing bottles, with ground glass stoppers.
- ii) Volumetric ware: 200 ml and 20 ml measuring cylinder.
2 conical flasks : 500 ml capacity.
2 x 5 ml burettes.

Method

- i) A small soil sample from the air-dry fine-earth fraction is randomly taken and placed in a pre-weighed weighing bottle (weighed to 0.001 g). Sample weight should be between 5.0 g and 0.2 g, depending on organic content (see Note 1). Reweigh the weighing bottle and note the weight of the soil sample (W).
- ii) Transfer the soil sample to a dry 500 ml conical flask. Run 10 ml of potassium dichromate N solution into conical flask

from the burette. Measure 20 ml of conc. H_2SO_4 in measuring cylinder and add to flask. Swirl the mixture for 1 minute and stand for 30 minutes to allow oxidation.

(iii) Add 200 ml of distilled water to the mixture, followed by 10 ml of orthophosphoric acid and 1 ml of indicator. Shake the mixture thoroughly. Titrate with ferrous sulphate solution, adding ferrous sulphate in 0.5 ml increments until colour changes from purple to green. Add a further 0.5 ml of dichromate, reversing the colour to purple. Ferrous sulphate is added, drop by drop, until the colour change is repeated. Note total volume of ferrous sulphate used (Y).

(iv) Standardise the ferrous sulphate.

Run 10 ml of potassium dichromate (N) solution from a burette into a 250 ml conical flask. Add 20 ml conc. H_2SO_4 . Allow mixture to cool. Add ferrous sulphate in 0.5 ml increments until colour of solution changes from purple to green. Add a further 0.5 ml of potassium dichromate, changing the colour back to purple. Add ferrous sulphate, drop by drop until the colour change is repeated. Note total volume of ferrous sulphate used (X). The ferrous sulphate solution should be standardised weekly.

Calculations

i) Total volume (V ml) of potassium dichromate used to oxidise the sample is given by :-

$$V = 10.5 \cdot (1 - Y/Z) \text{ ml}$$

where Y = total volume of ferrous sulphate used in the test.

X = total volume of ferrous sulphate used in the standardisation.

ii) Percentage organic matter.

$$\text{Organic matter content (\% by weight)} = \frac{0.67 \cdot V}{W}$$

where W = weight of sample.

Notes

1) Sample size.

Sample size varies with organic content. 5 g may be required for soil with low organic matter while 0.2 g may suffice with organic soils. Since the soils tested were usually of a peaty nature samples of 0.2 - 0.25 g were used.

2) Procedural modification.

The procedure described is a modified version of that described by the British Standards Institution (1967). The B.S.I. procedure employs soil finer than $\frac{3}{8}$ in (9.53 mm) in diameter. Thus, the equation is :-

$$\frac{0.67 W_2 V}{W_1 \cdot W_3}$$

where W_1 = weight of sample before sieving.

W_2 = weight of sample passing $\frac{3}{8}$ inch (9.53 mm) B.S. test sieve.

W_3 = weight of soil sample used in the test.

In this study the organic component of the fine-earth fraction is investigated. Thus W_1 and W_2 are not used, hence giving the simpler equation described.

APPENDIX IV

TEXTURAL ANALYSIS OF SOIL FINE-EARTH FRACTIONS

Pre-treatment

- i) Removal of organic matter.
Place an air-dried soil sample, of about 30 g, in a 500 ml beaker. Add 100 ml of hydrogen peroxide (20 vol) and gently warm. Add more hydrogen peroxide until frothing ceases.
- ii) Transfer the residue to a weighed evaporating basin and oven dry. Determine the oven-dry weight of the sample.
- iii) Pipette 100 ml of sodium hexametaphosphate solution (Calgon) into the soil container. The calgon solution should have a concentration of 40 g l^{-1} . Warm mixture for 10 minutes and disperse in ultra-sonic bath for 10 minutes.
- iv) Wet sieve the sample through a $63 \mu\text{m}$ sieve using a jet of water.
- v) Material retained by the $63 \mu\text{m}$ sieve is then air-dried. Ground the dry soil and dry sieve, on $1000 \mu\text{m}$, $212 \mu\text{m}$ and $63 \mu\text{m}$ sieves. Record the weight of material retained by each sieve.

Pipette procedure

- i) Transfer the material which has passed through the $63 \mu\text{m}$ sieve, both by wet and dry sieving, to a 500 ml sedimentation cylinder. Fill the cylinder up to the 500 ml mark with distilled water.
- ii) Allow the suspension to gain a constant temperature by standing overnight in the water bath. Shake the cylinder vigorously for 1 minute immediately prior to commencing observations.

- iii) After 1 minute lower the pipette into the suspension to a depth of 10 cm and withdraw a 25 ml sample. Transfer sample to a weighed weighing bottle and oven dry. Record the oven-dry weight of the sample.
- iv) Repeat procedure (iii) at prescribed time-intervals. The time-interval is determined using the calibration curve of Akroyd (1964). Assuming a sediment specific gravity of 2.65 and a constant temperature of 20°C the sampling times for various effective diameters are :-

	<u>Effective diameter (mm)</u>	<u>Settling time</u>
Coarse silt	0.040	1' 12"
Medium silt	0.020	4' 44"
Fine silt	0.006	52' 31"
Clay	0.002	7' 52"

Calculations

- i) The percentage material less than a given size is calculated using the equation :-

$$\% \text{ material } < \text{ effective diameter } X = \left(\frac{W \times V}{v} - W. \text{ Cal} \right) \frac{100}{W_1}$$

where X = Effective diameter (determined by sampling time).

W_X = Weight of material withdrawn by pipette at time equivalent to effective diameter X.

V = Volume of pipette (25 ml)

v = Volume of sedimentation cylinder (500 ml)

W.Cal = Weight of calgon added to sedimentation cylinder (weight approximately 4 g, but is determined by evaporation for each bottle of Calgon).

- ii) Display results as a cumulative curve on semi-log paper.

APPENDIX V

DETERMINATION OF THE CATION EXCHANGE CAPACITY
OF THE FINE-EARTH FRACTIONS

Reagents

- i) Buffered Barium Chloride (BaCl_2) reagent.
Dilute 90 ml of Triethenolamine solution to 1 l and adjust pH to 8.1 by adding approximately 140 ml 2 N HCl. Dilute to 2 l. Mix with an equal portion of BaCl_2 solution.
- ii) Magnesium sulphate solution 0.05 N.
Dissolve 6.2 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ in 1 l of distilled water.
- iii) Ammonia (NH_4OH) (2 N).
- iv) Standard E.D.T.A. solution.
- v) Indicator. Either Catechol violet indicator (Bascomb, 1964) or Omega chrome black indicator (Avery and Bascomb, 1974).

Procedure

- i) Weigh 5 g of fine-earth soil sample into a polythene centrifuge bottle. Record weight (M_1). Pipette 200 ml of buffered barium chloridge reagent into bottle and stand overnight. Centrifuge at 1500 r.p.m. for 15 minutes. Discard supernatent liquid. Add 200 ml of distilled water for washing, shake and centrifuge at 1500 r.p.m. for 15 minutes. Discard supernatent liquid and reweigh soil (M_2).
- ii) Pipette 100 ml of MgSO_4 into bottle. Shake the stoppered bottle at intervals over a 2 hour period. Centrifuge and decant the supernatent liquid.
- iii) Add 2 drops of ammonia and 2 drops of indicator to a 5 ml aliquot of the supernatent liquid. Titrate with standard

E.D.T.A. Note volume needed (Titre A_1 ml) to change colour from red to blue. Treat a 5 ml aliquot of $MgSO_4$ similarly (Titre B ml).

Calculations

- i) The soil titre (A_1) must be corrected for the effect of the volume of liquid retained by the centrifuged soil after the water wash. Thus :-

$$\text{corrected titre } (A_2) = A_1 (100 + M_2 - M_1)/100 \text{ ml.}$$

- ii) Cation Exchange Capacity CEC in meq/100 g is calculated using the equation

$$\text{CEC} = 8 (B - A_2) \text{ meq/100 g.}$$

Procedural modification for the determination of the Cation Exchange Capacity of the clay fraction

- i) Preparation. Extract a clay separate using standard pipette procedures (cf. Appendix IV).

- ii) Method. Weigh 0.500 g of oven-dried clay into a 50 ml polypropylene centrifuge tube. The procedure is as above, but 25 ml volumes of buffered barium chloride and water are used and 20 ml $MgSO_4$.

- iii) Calculations.

Corrected titration (A_2 ml) is calculated using the equation

$$A_2 = A_1 \left(\frac{20 + M_2 - M_1}{20} \right)$$

Cation Exchange Capacity (meq/100 g) is calculated as

$$\text{CEC} = 16 (B - A_2)$$

APPENDIX VI

DETERMINATION OF SPECIFIC GRAVITY OF SOIL SAMPLES

Procedure

- i) Grind a soil sample in a stone pestle and weigh out a sample of 5-10 g. Place sample in a weighed 25 ml specific gravity bottle.
- ii) Partially fill the S.G. bottle with boiled (i.e. air-free) distilled water and place in a vacuum desiccator. Gently evacuate.
- iii) Release vacuum slowly and remove bottles. Top up with air-free distilled water. Weigh bottles.
- iv) Wash out bottles and refill with distilled water. Wipe and dry. Reweigh bottles.

Calculations

- i) Wt. of S.G. bottle
- $\frac{\text{Wt. of S.G. bottle} + \text{wt. soil}}{\text{Wt. of soil}}$
- ii) Wt. of S.G. bottle, soil, water.
- $\frac{\text{Wt. of S.G. bottle and wt. soil}}{\text{Wt. of water added to sample}}$
- iii) Wt. of S.G. bottle + water
- $\frac{\text{Wt. of S.G. bottle}}{\text{Wt. of water (i.e. volume non-solid matter)}}$
- iv) S.G. of soil sample = $\frac{\text{Wt. of soil}}{\text{Volume of soil}}$

APPENDIX VII

EGTON HIGH MOOR AIR TEMPERATURE DATA

EACH LINE REFERS TO ONE DAY'S DATA.

DATA BEGINS ON SEPTEMBER 1, 1978 (CASE 0) AND ENDS ON AUGUST 31, 1979 (CASE 364).

THE FIRST 6 VALUES ARE FOR THE HEATHER PROBE AND THE SECOND 6 FOR THE BURNT GROUND PROBE.

THE VALUES ARE FOR MAXIMUM, MINIMUM, MEAN AND MAXIMUM VARIATION IN DAILY TEMPERATURE ($^{\circ}\text{C}$), NUMBER OF FREEZE-THAW CYCLES AND DURATION OF SUB-ZERO TEMPERATURES (HOURS).

MISSING VALUES ARE DENOTED BY 99.

DAMAGED

TEXT

IN

ORIGINAL

0 101 5.5 7.3 4.0 0 0 15 2.6 1.5 17.4 0 0
1 121 7.9 6.5 1 0 0 18 5.5 4.1 17.5 0 0
2 164 5.6 1 2 11.2 0 0 24 3 13.5 27 0 0
3 161 7.2 1 7 6.9 0 0 6.9 1 17.6 5.3 14.0 11.0 0 0
4 164 6.1 1 1.3 10.3 0 0 26.1 2.6 13.4 21.5 0 0
5 131 7 10.1 6.1 0 20 5.1 12.5 14.1 0 0
6 162 7.7 6.7 2 0 0 9.8 7.2 8.5 2.0 0 0
7 162 7.4 12.8 4 0 23.7 5.2 14.5 10.5 0 0
8 184 9.6 12.2 12.4 0 0 28.1 15.5 25 0 0
9 149 9.4 12.5 0 0 10.4 7.8 13.7 11.0 0 0
10 171 10 13.6 7.1 0 19.5 13.6 11.6 11.0 0 0
11 152 9.4 12.5 5.4 0 25.0 8.5 17.2 17.3 0 0
12 131 7.4 1.5 11.3 0 0 20.1 5.1 12.6 15 0 0
13 131 8 10.6 5.1 0 0 2.2 4.2 11.7 15 0 0
14 177 6 11.3 7.4 0 0 20.1 5.1 12.6 15 0 0
15 177 6 11.3 7.4 0 0 20.1 5.1 12.6 15 0 0
16 145 5.8 10.1 2.8 7 0 20.3 3 11.6 17.2 0 0
17 155 9 12 0 26.2 0 11.6 25.2 1 2
18 155 11.5 13 0 25.1 11.6 25.2 1 2
20 21 11 16.1 9.9 0 22 16.1 27 0 0
21 152 11 13.1 4.2 0 19.5 5.3 12.6 14.6 0 0
22 18 13 16.5 0 0 27.5 5.4 16.5 22.1 0 0
23 17 2 12.1 9.8 0 23 6.3 14.7 10.7 0 0
24 13 4 6.7 1.1 6.7 0 12.5 4.4 11.7 14.0 0 0
25 13 4 6.7 1.1 6.7 0 12.5 4.4 11.7 14.0 0 0
26 12 4 6.8 0.7 0 0 18.2 2.1 10.6 15.3 0 0
27 10 5 6.4 8.7 3.7 0 13.5 3.6 5.6 4.0 0 0
28 10 5 6.4 8.7 3.7 0 13.5 3.6 5.6 4.0 0 0
29 11 2 7.5 0 0 13.9 2.2 4 11 0 0
30 11 2 7.5 0 0 13.9 2.2 4 11 0 0
31 11 2 7.5 0 0 13.9 2.2 4 11 0 0
32 14 6.1 9.1 9.9 0 17.2 4 11 3 11.8 0 0
33 14 6.1 9.1 9.9 0 17.2 4 11 3 11.8 0 0
34 14 6.1 9.1 9.9 0 17.2 4 11 3 11.8 0 0
35 16 5 3 11.9 1.3 0 14.0 4.4 7 10.5 0 0
36 11 5 8.2 6.4 0 13.0 2.4 8.5 8.1 0 0
37 00 0 0 0 0 0 0 0 0 0 0 0 0 0
38 00 0 0 0 0 0 0 0 0 0 0 0 0 0
39 14 4 9 1 11.8 5.3 0 0 17.7 12 10 0 0
40 20 3 10.5 15.6 9.8 0 22.1 18.6 10.9 16.6 0 0
41 12 1 1 15.1 15.9 0 0 30 21 11.6 26.0 0 0
42 12 1 1 15.1 15.9 0 0 30 21 11.6 26.0 0 0
43 12 1 1 15.1 15.9 0 0 30 21 11.6 26.0 0 0
44 0 1 7.6 2.9 0 0 8.4 6.4 3.2 0 0
45 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
46 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
47 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
48 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
49 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
50 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
51 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
52 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
53 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
54 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
55 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
56 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
57 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
58 8 1 5 9 1 7 0 8.8 0 0 5.5 7 0 0
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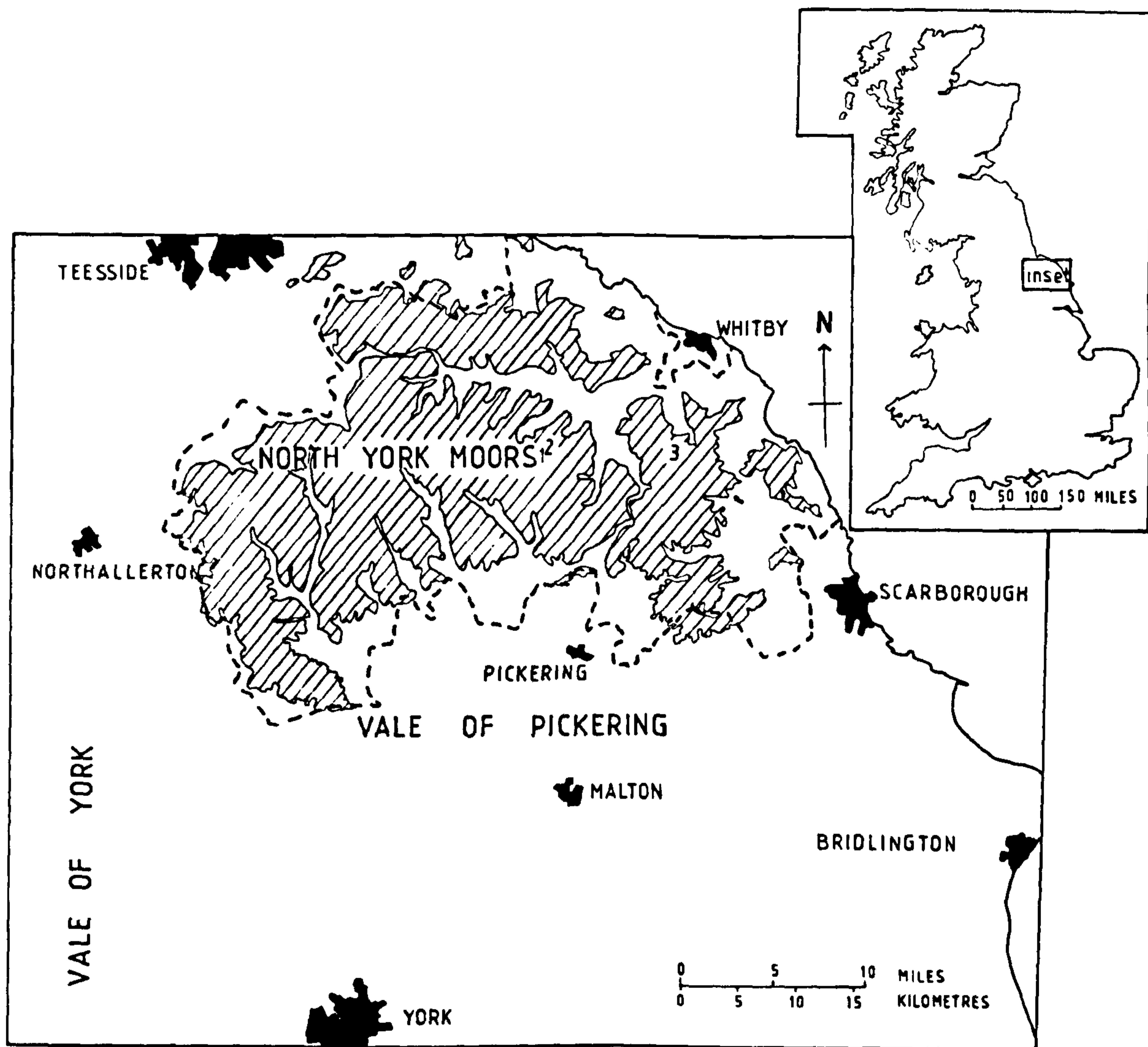
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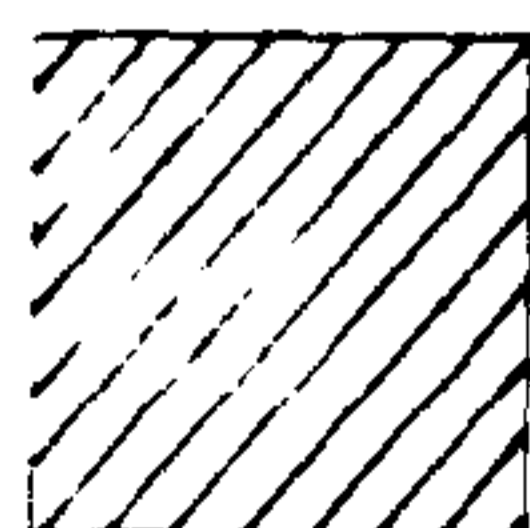
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- 1 WINTERGILL CATCHMENT
- 2 EGTON HIGH MOOR SOIL PLOTS
- 3 SNEATON HIGH MOOR SOIL PLOTS



LAND ABOVE 600 FEET (183 METRES) O.D.



NATIONAL PARK BOUNDARY

Fig. 1 Location of field sites.

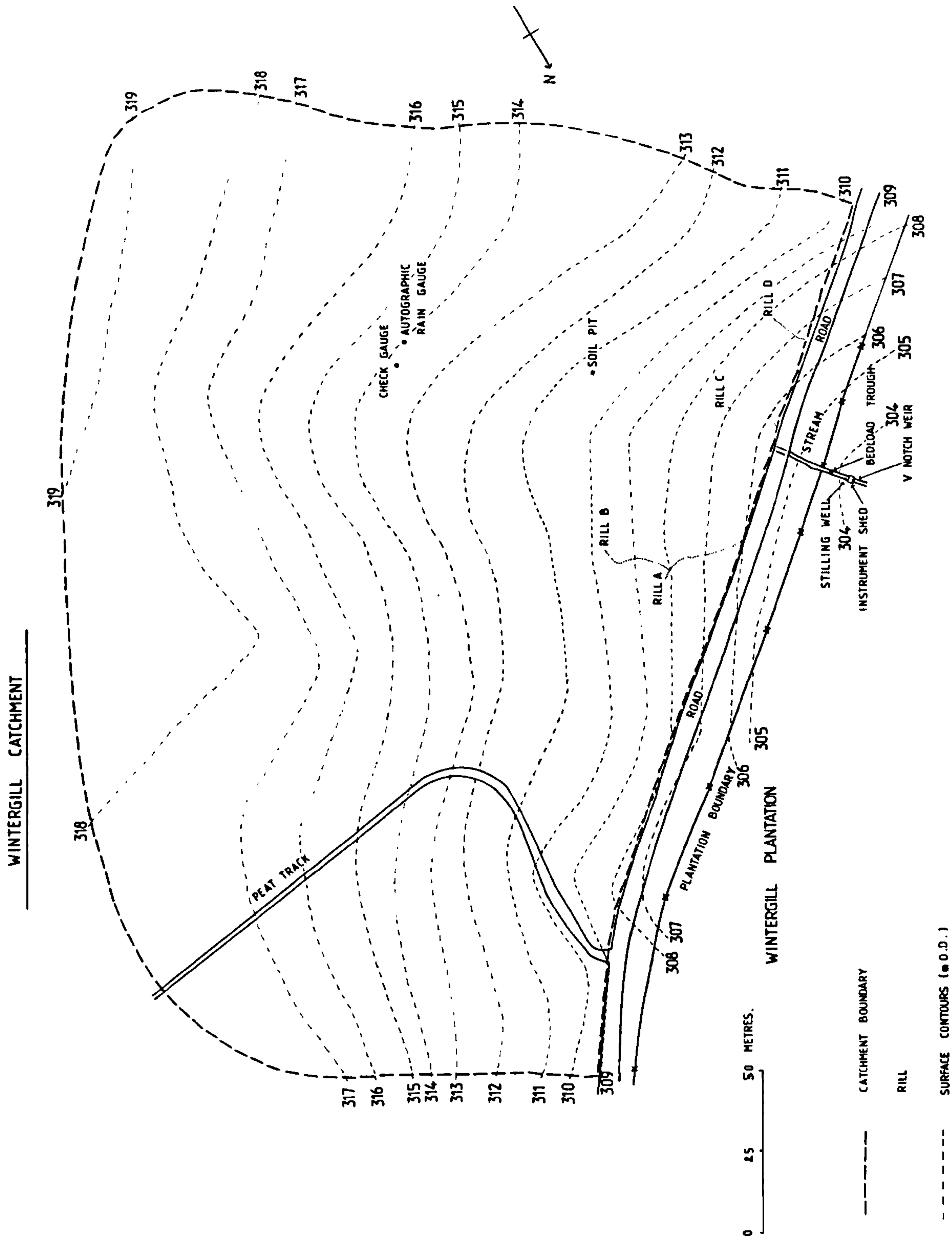


Fig. 2 Wintergill Catchment.

EGTON HIGH MOOR

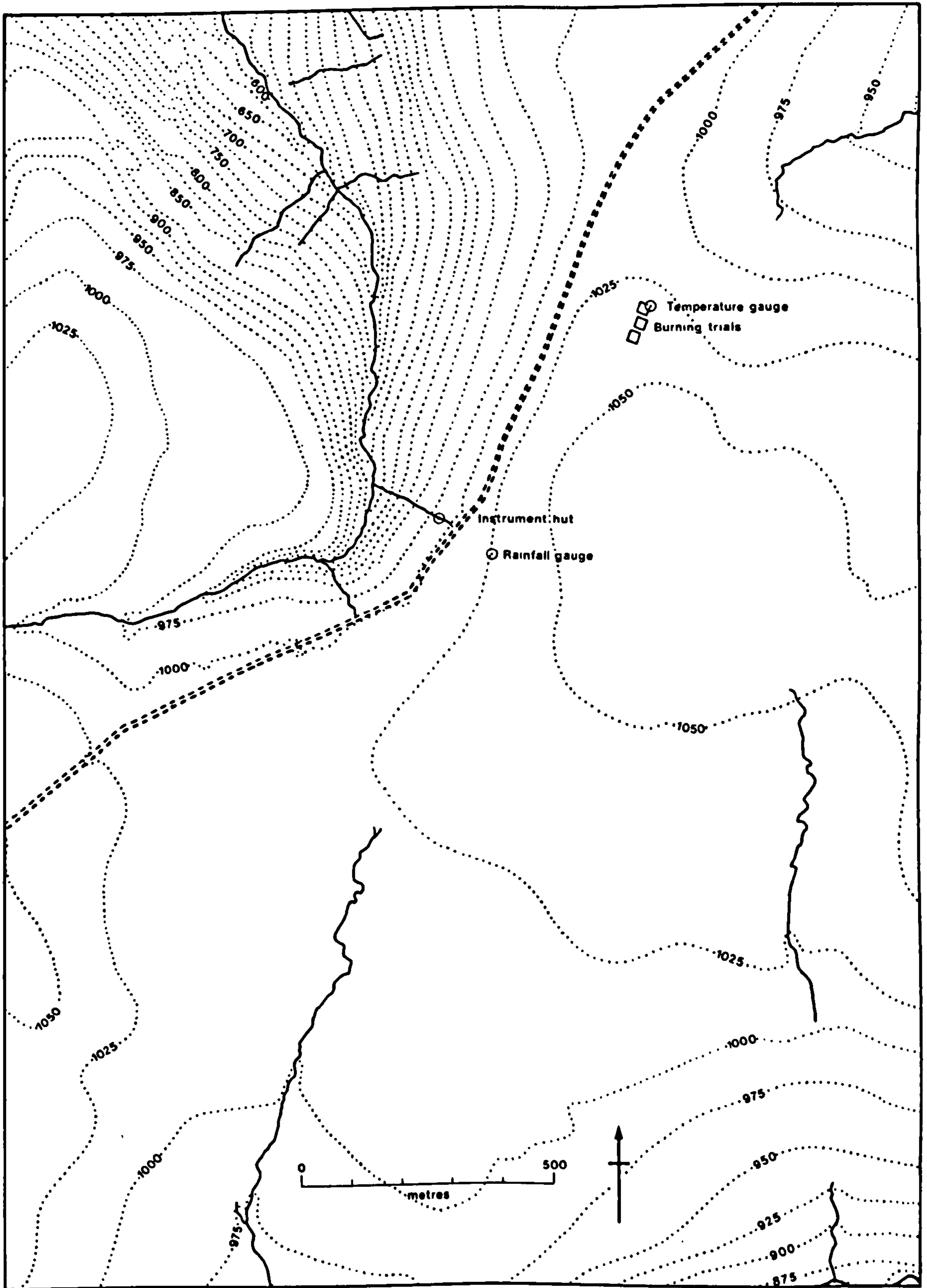
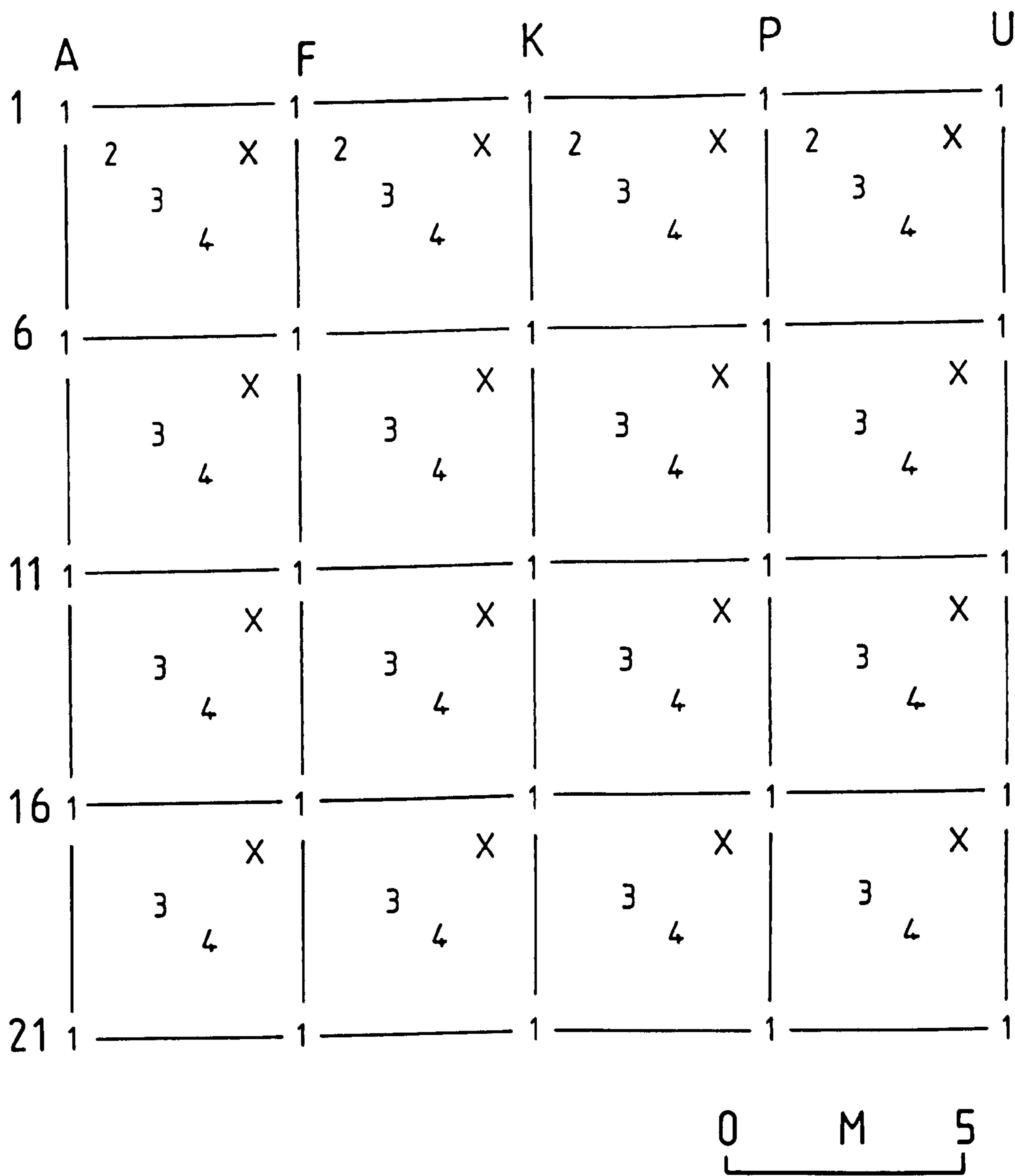


Fig. 3 Location of Egton High Moor soil plots.



SMALLER NUMBERS REFERS TO SOIL SAMPLING SEQUENCE.

X MARKS AN EROSION PIN LOCATION.

Fig. 4 Egton High Moor soil plots grid referencing system.

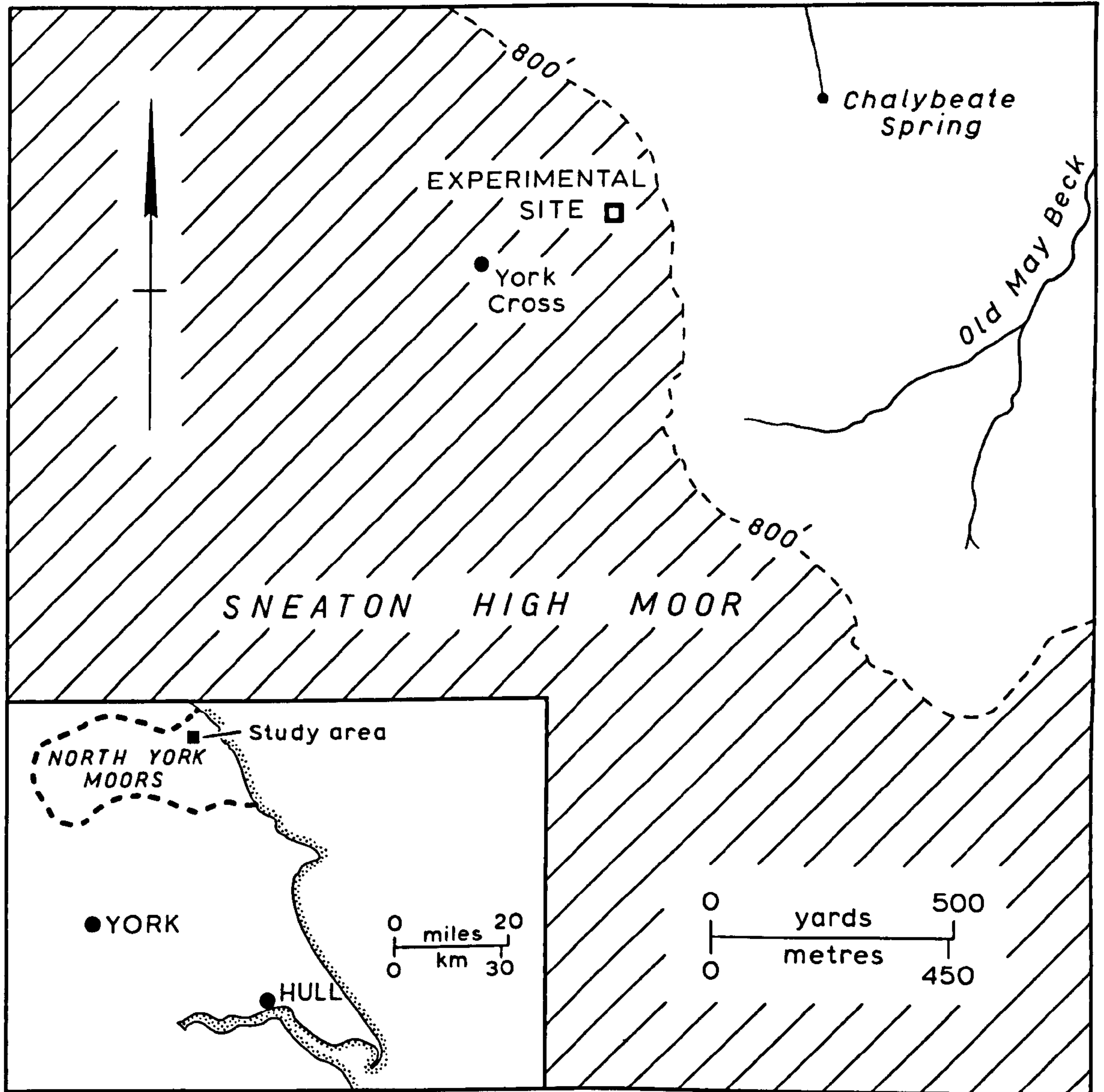


Fig. 5 Location of Sneaton High Moor radiation plots.

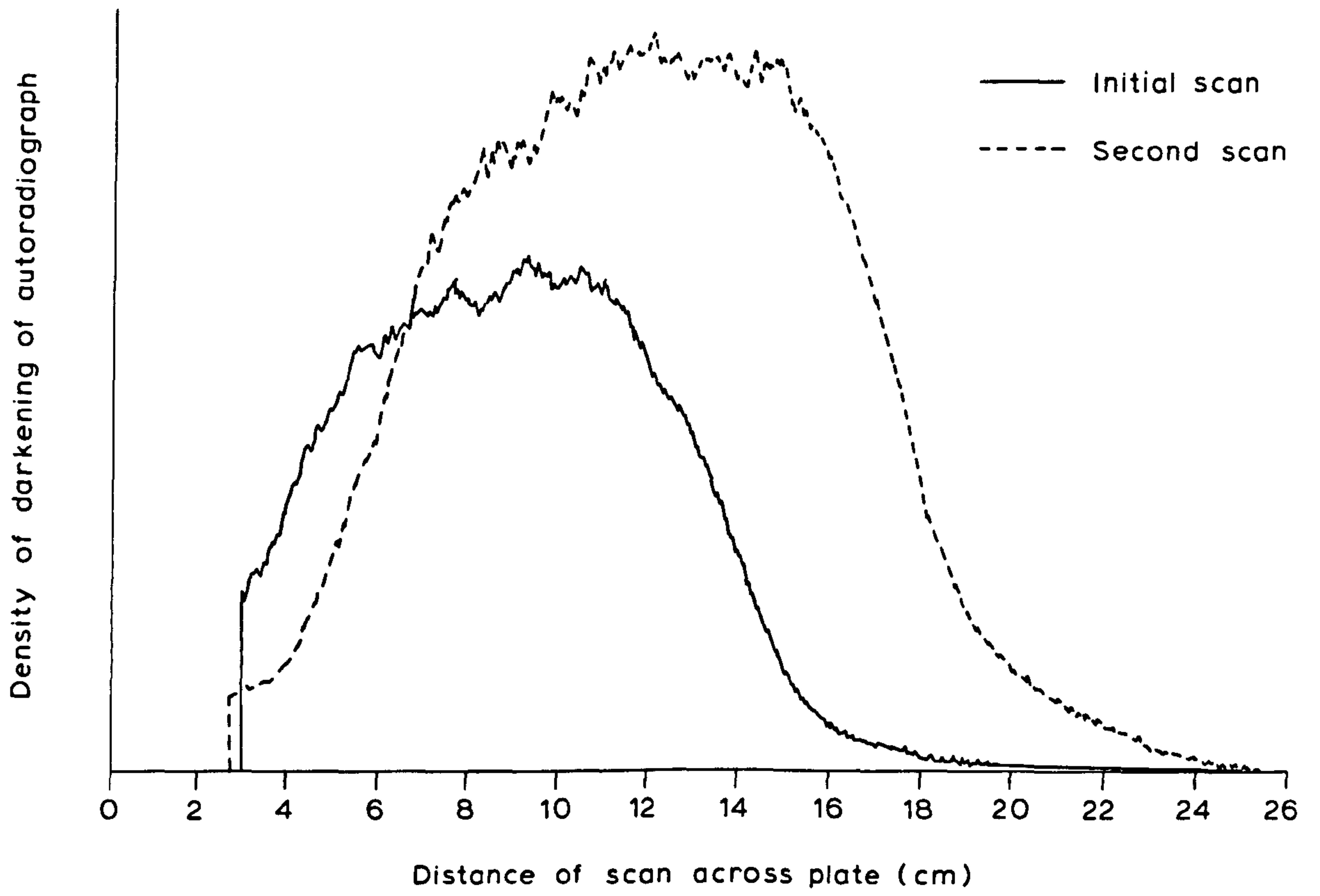


Fig. 6 Micro-densitometer recordings of scans across the autoradiographs.

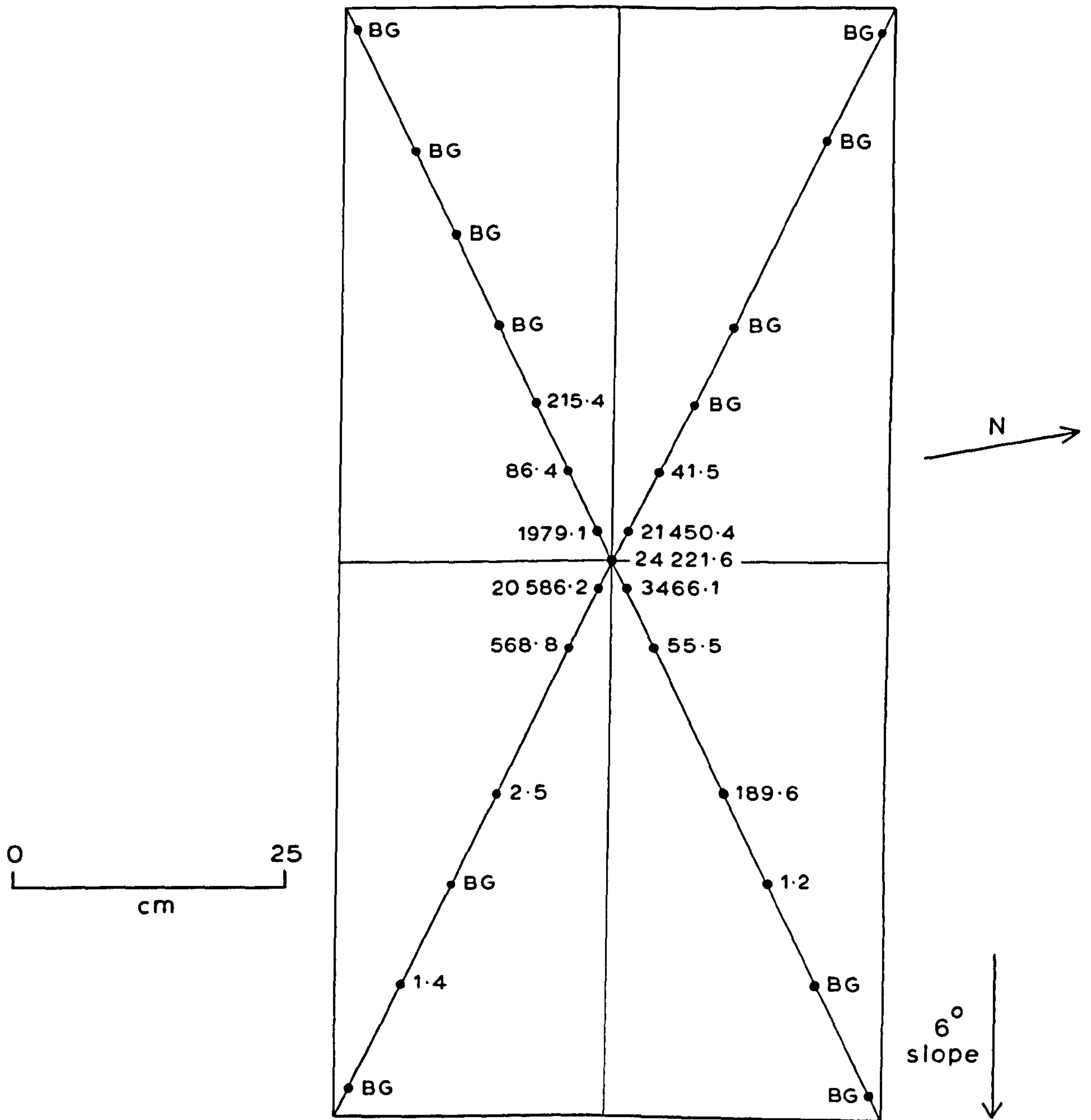


Fig. 7 Map showing count rates (C.P.M.) and sampling points after the exposure of radio-active soil.

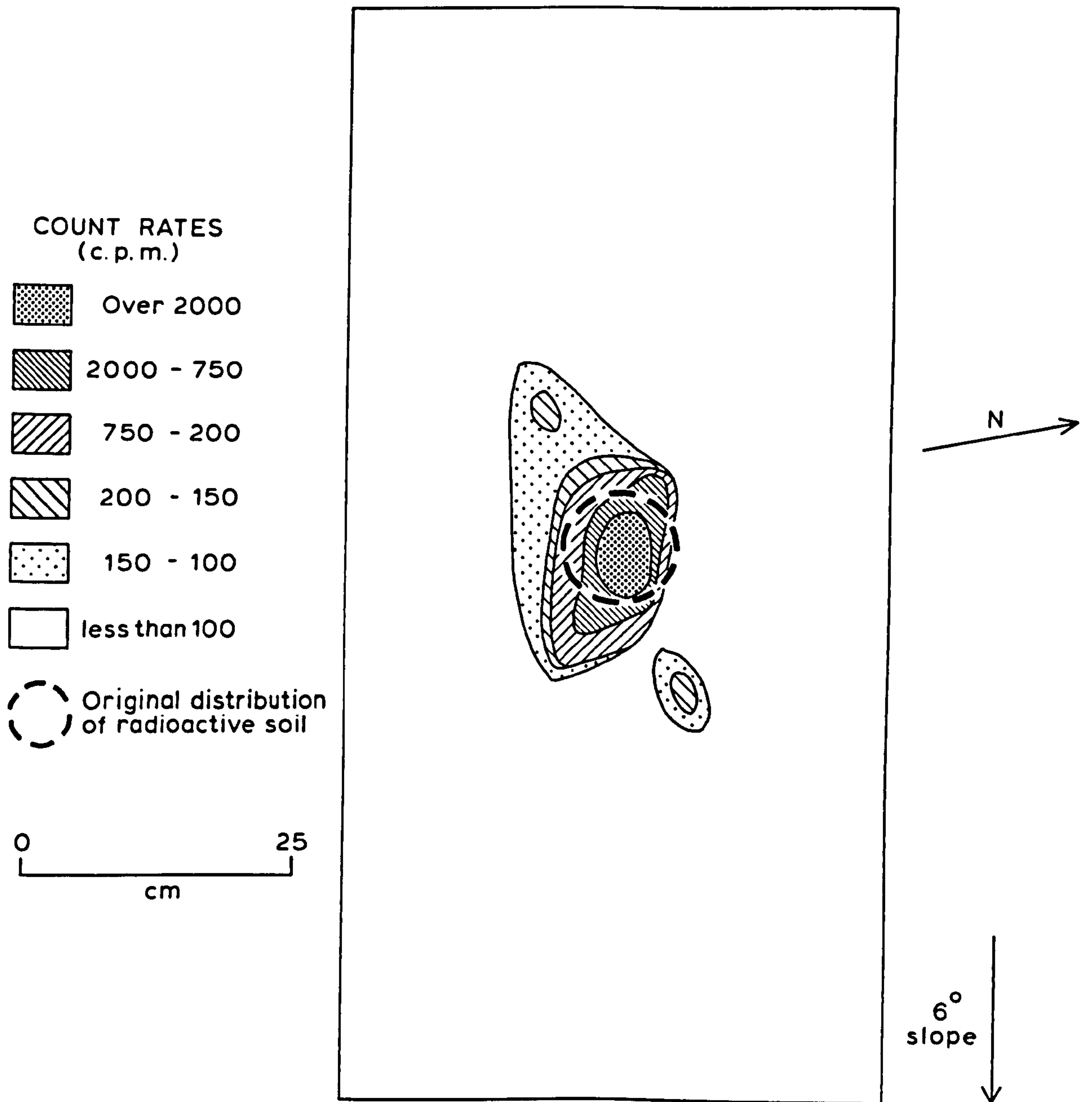


Fig. 8 Map of the distribution of radio-active soil.

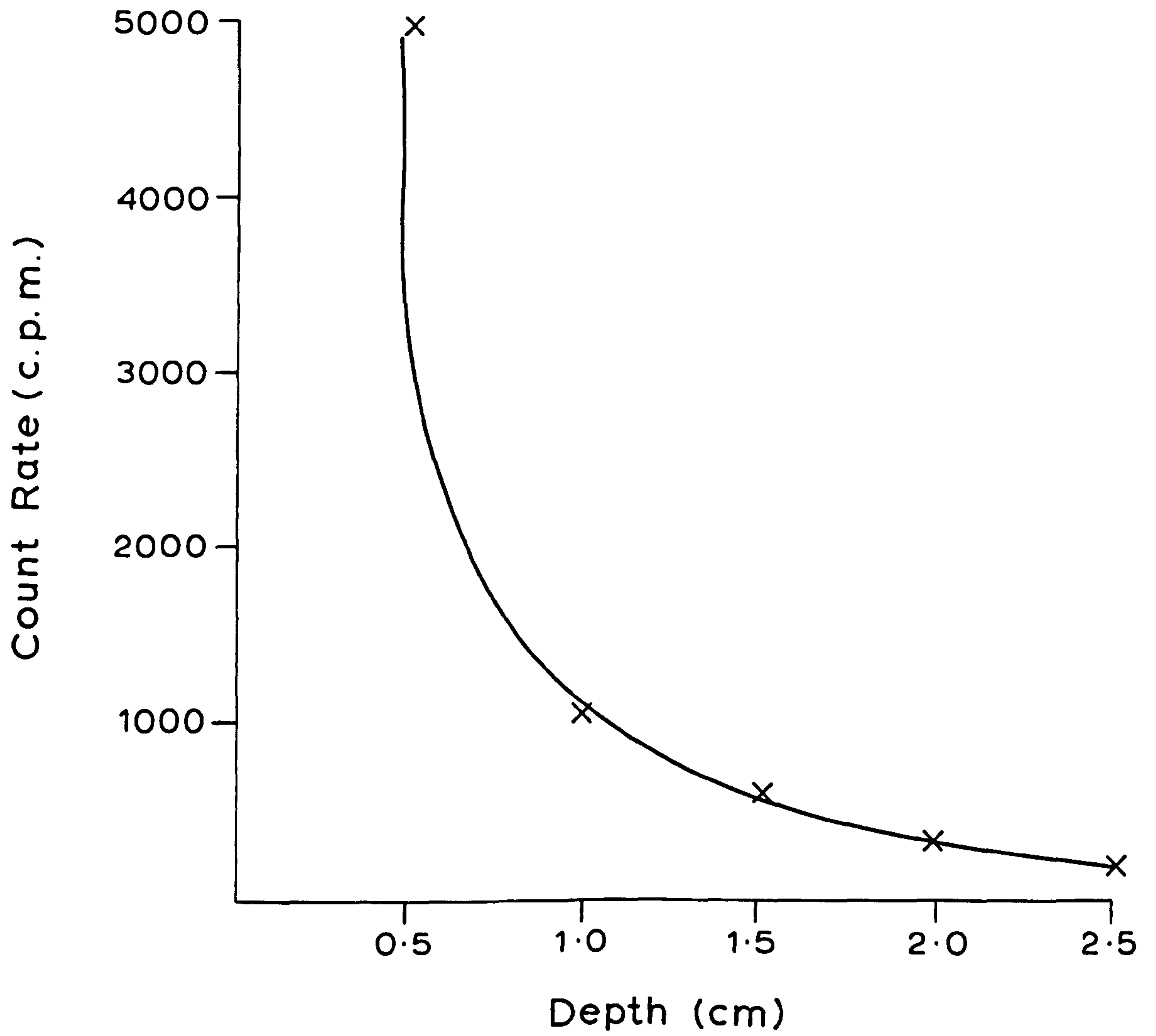
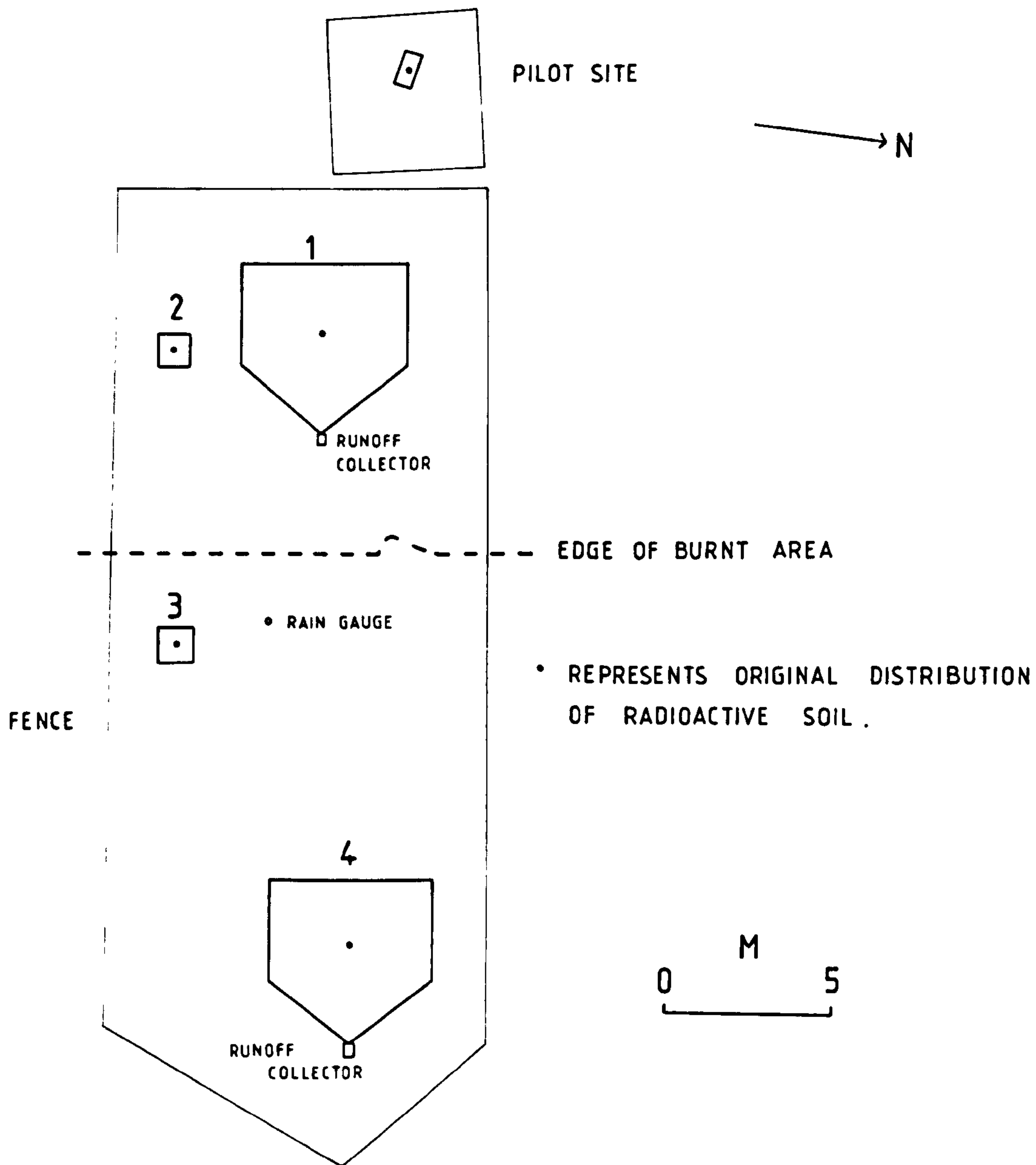


Fig. 9 Vertical distribution of radio-activity within core taken from the centre of the monolith.



- 1 VEGETATED RUNOFF PLOT
- 2 VEGETATED PLOT (6 MONTH EXPOSURE)
- 3 BURNT PLOT (6 MONTH EXPOSURE)
- 4 BURNT RUNOFF PLOT

Fig. 10 Plan of Sneaton High Moor radiation plots.

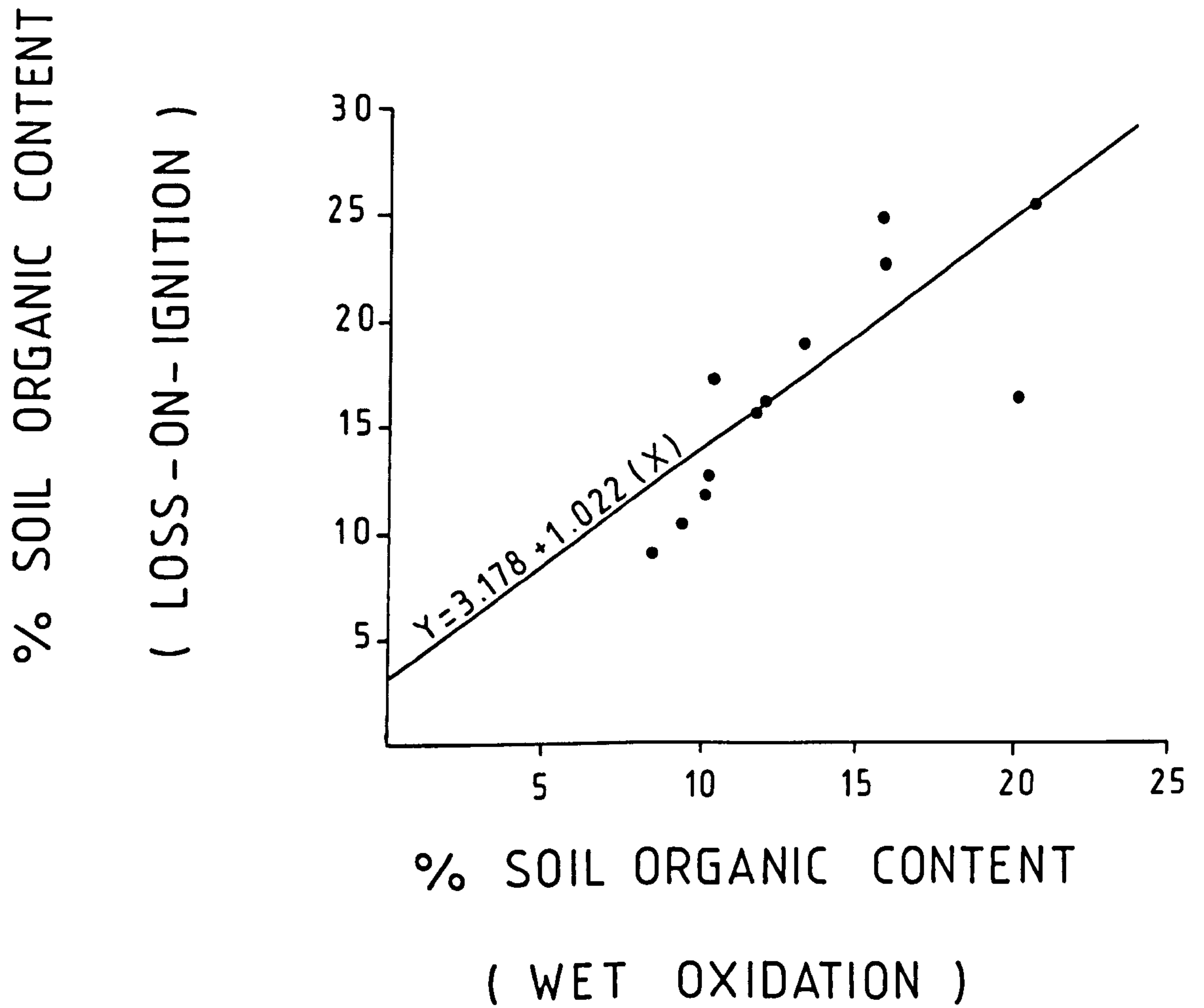
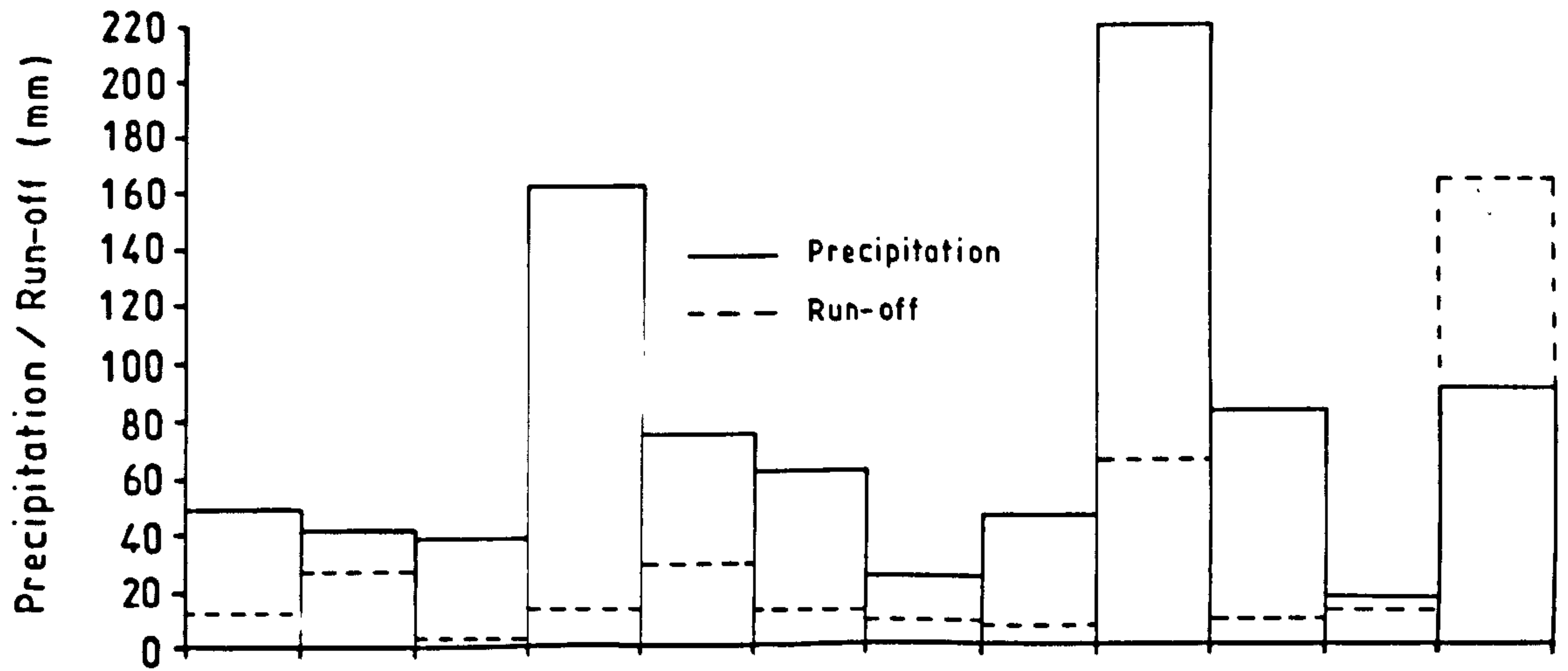


Fig. 11 Relationship between soil organic content determined by loss-on-ignition and wet oxidation.

Estimated Precipitation and Run-off from Wintergill Catchment



Estimated Run-off as a Percentage of Precipitation

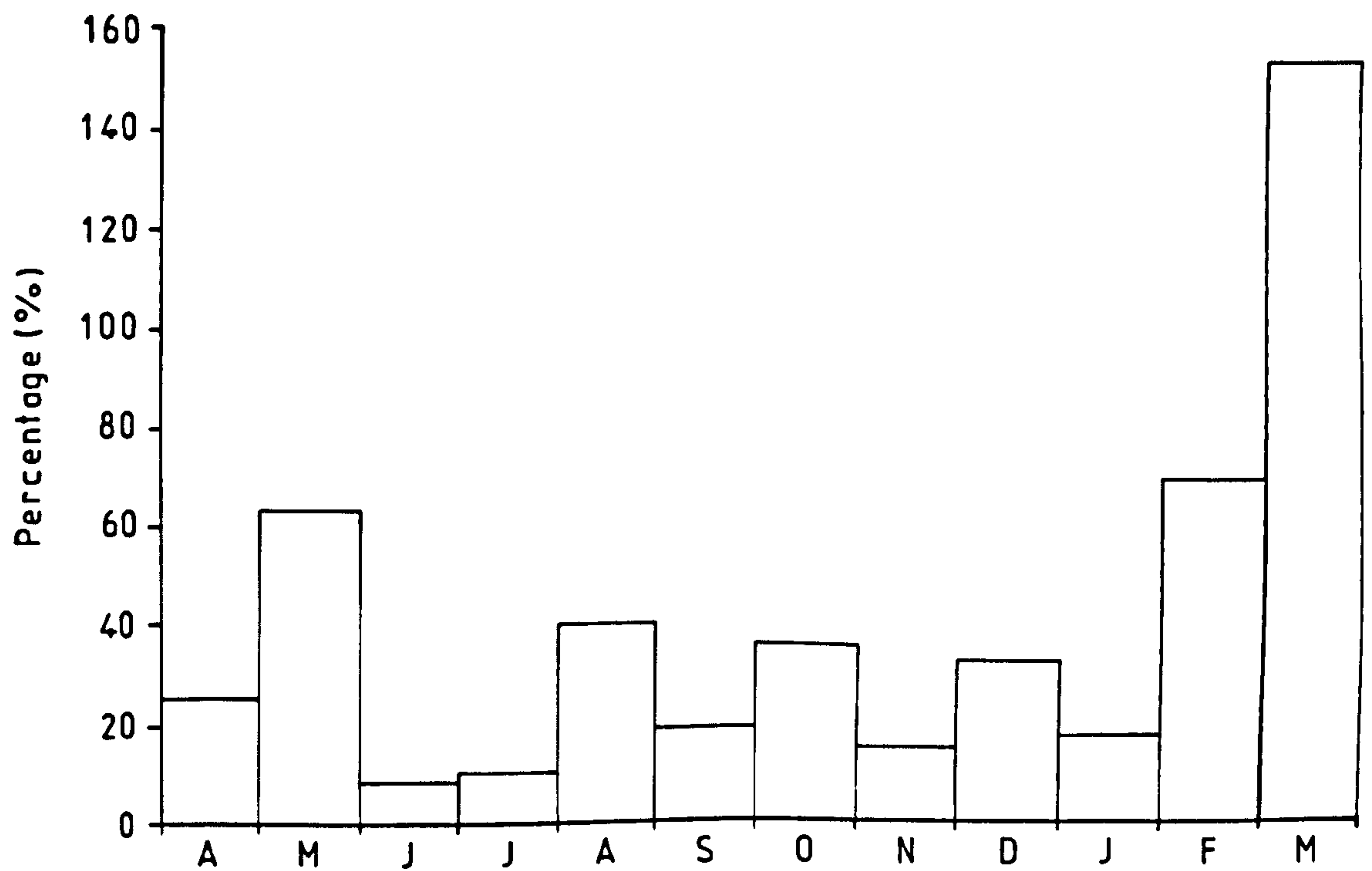


Fig. 12 (a) Estimated precipitation and run-off from Wintergill Catchment (April 1978 - March 1979).

Fig. 12 (b) Estimated run-off as a percentage of precipitation.

Annual streamflow duration curve of
Wintergill catchment

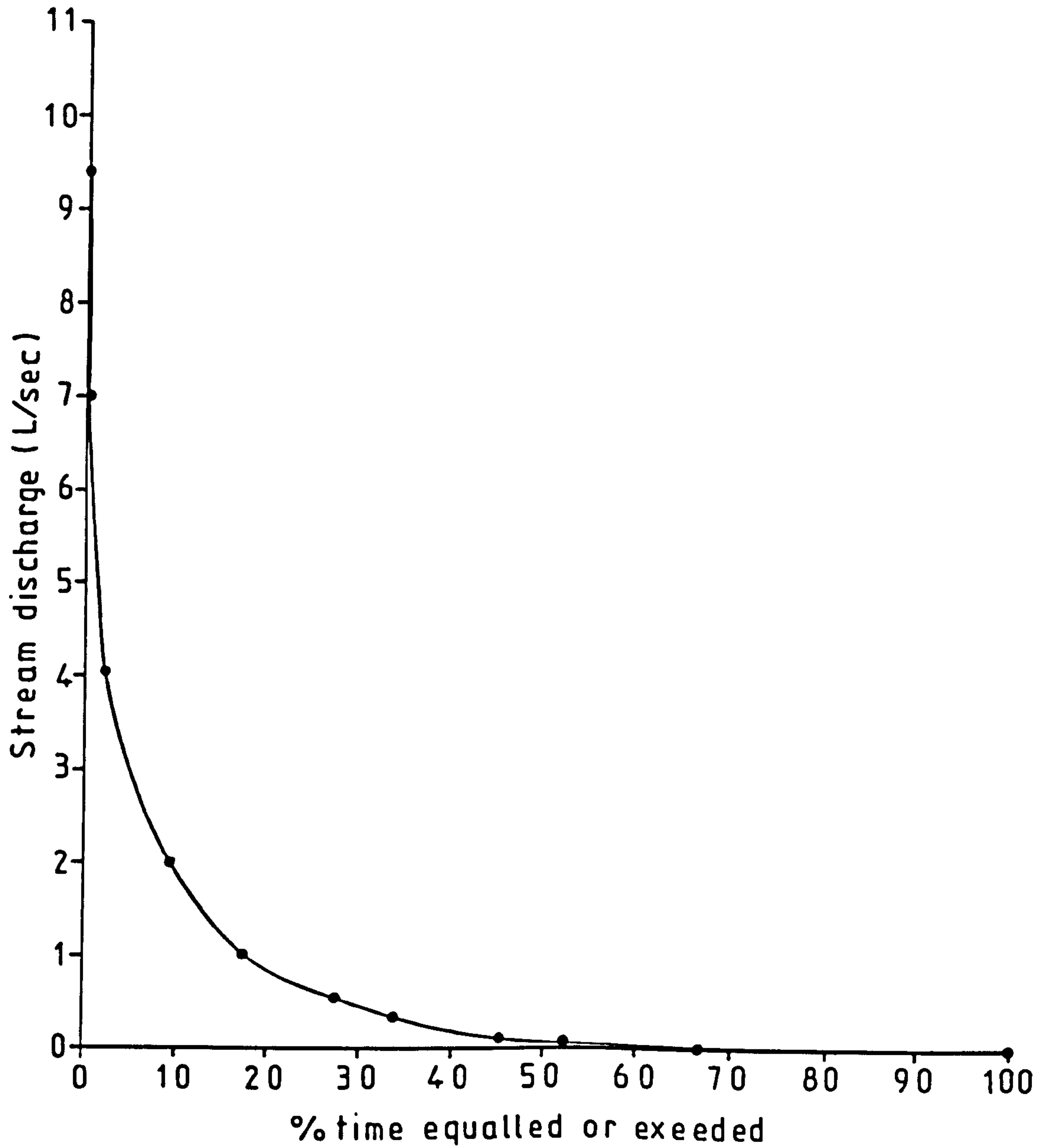


Fig. 13 Annual streamflow duration curve of Wintergill Catchment
(April 1978 - March 1979).

Plot of daily discharge and precipitation
within Wintergill catchment

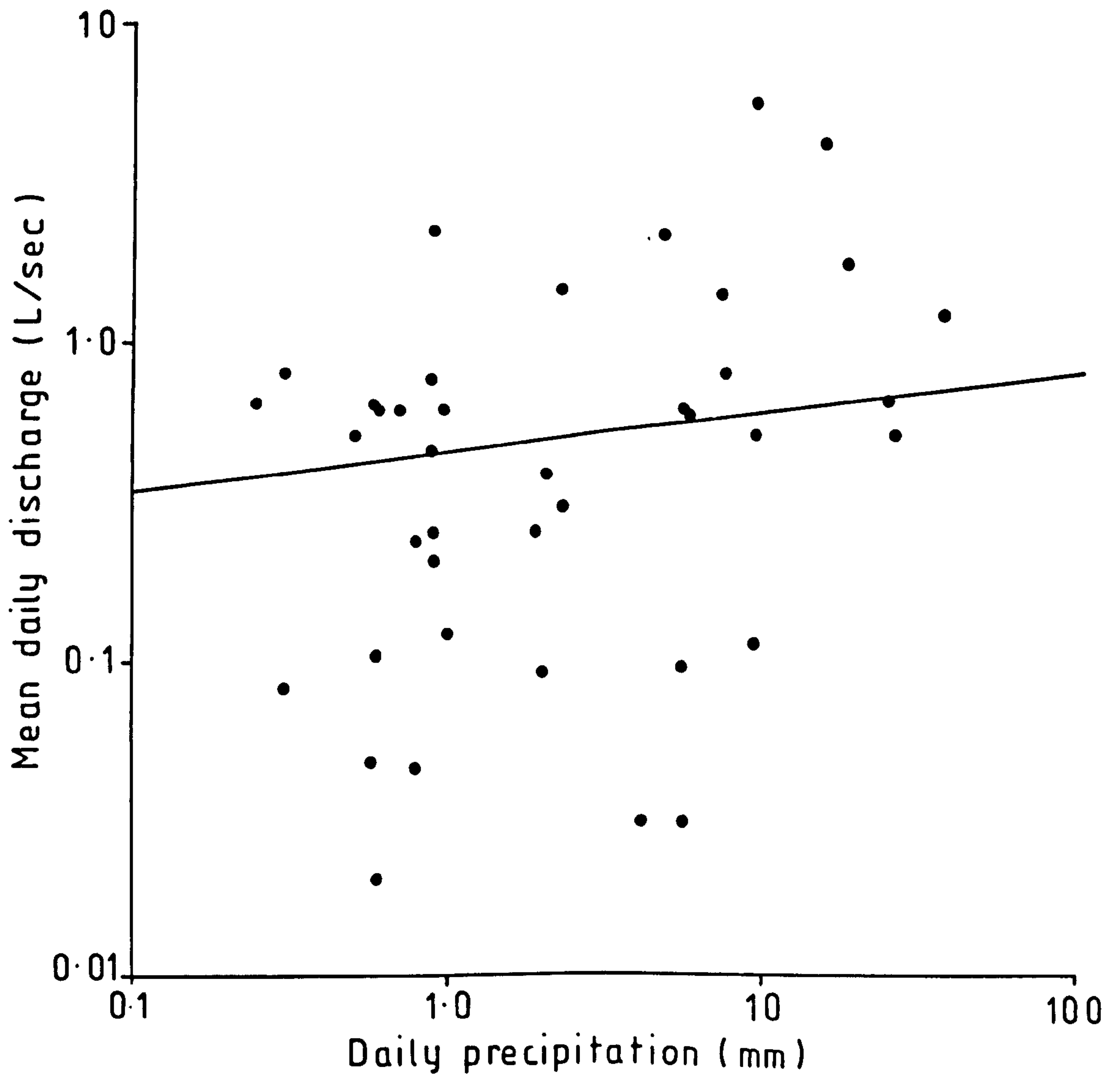


Fig. 14 Plot of daily discharge and precipitation within Wintergill Catchment.

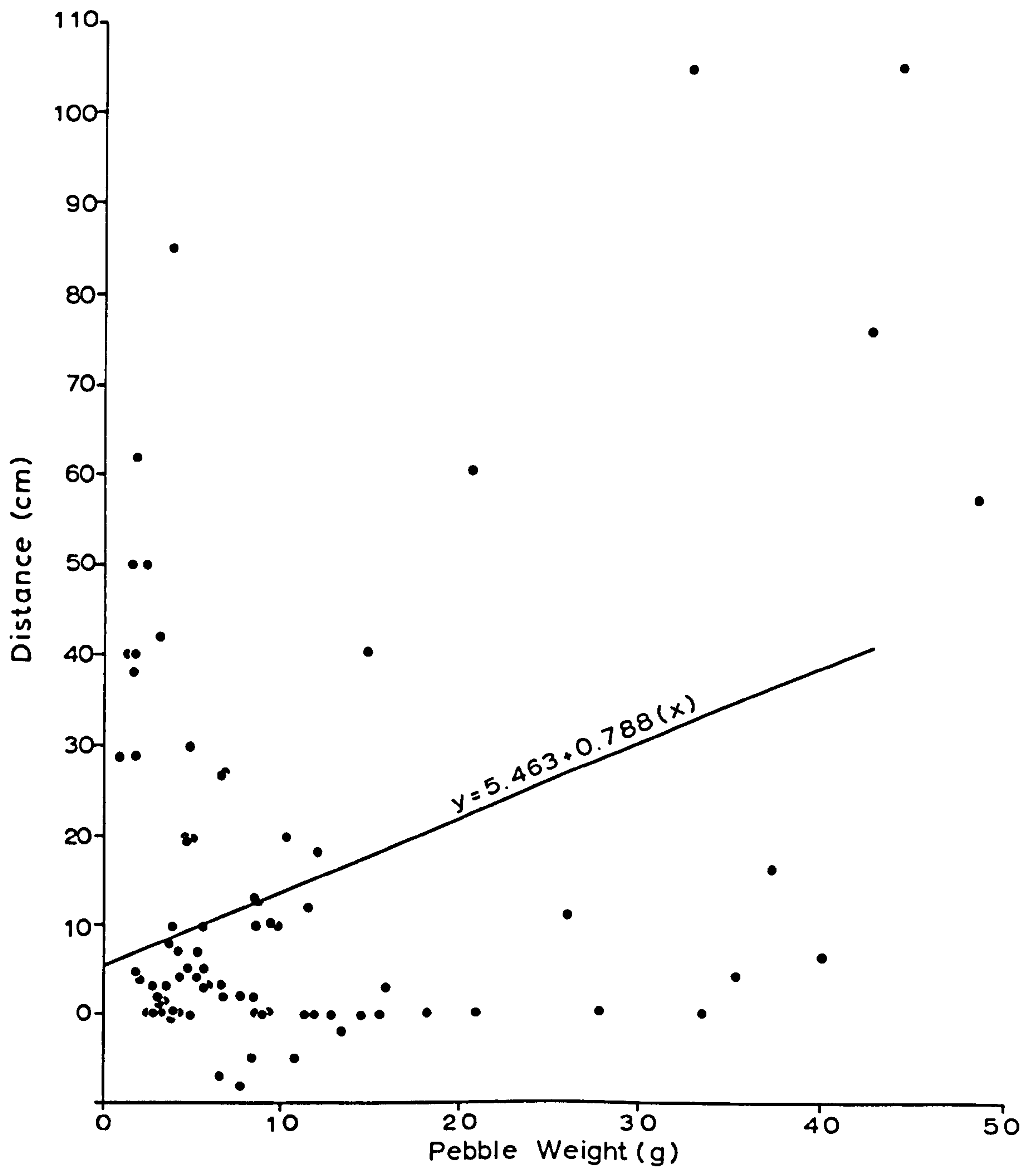


Fig. 15 The relationship between pebble weight and distance of pebble movement.

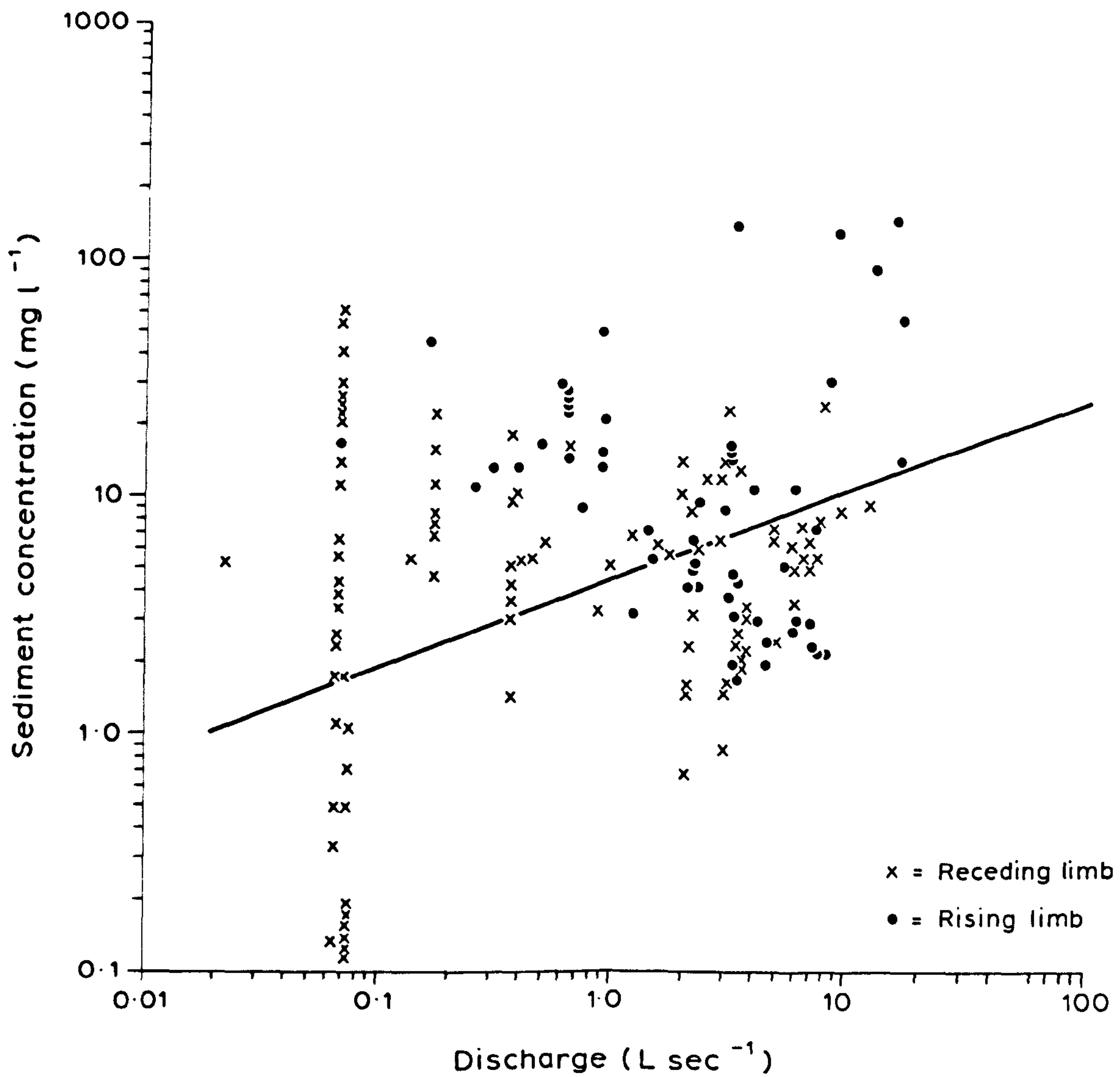


Fig. 16 The relationship between discharge (l sec⁻¹) and sediment concentration (mg l⁻¹).

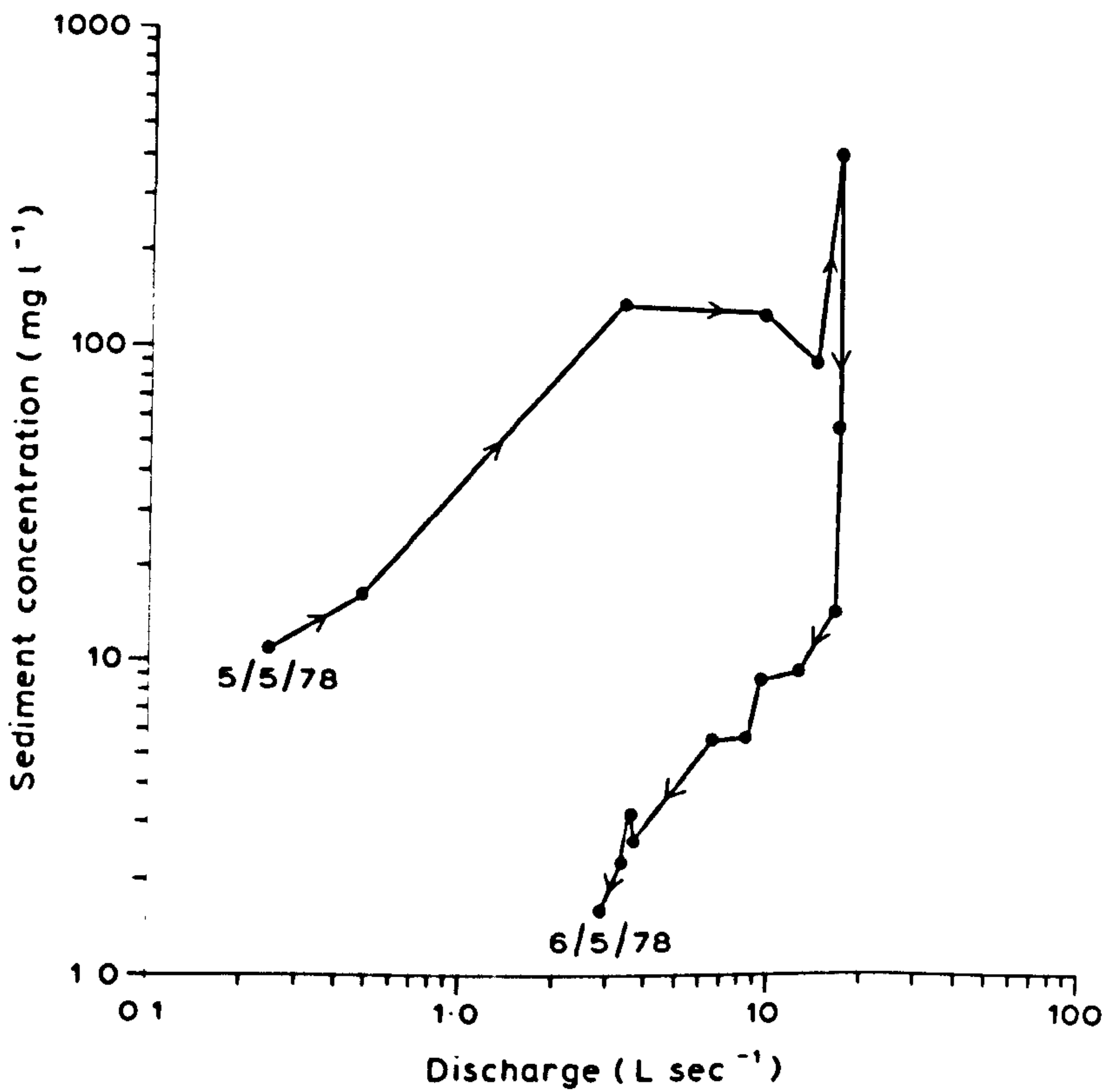
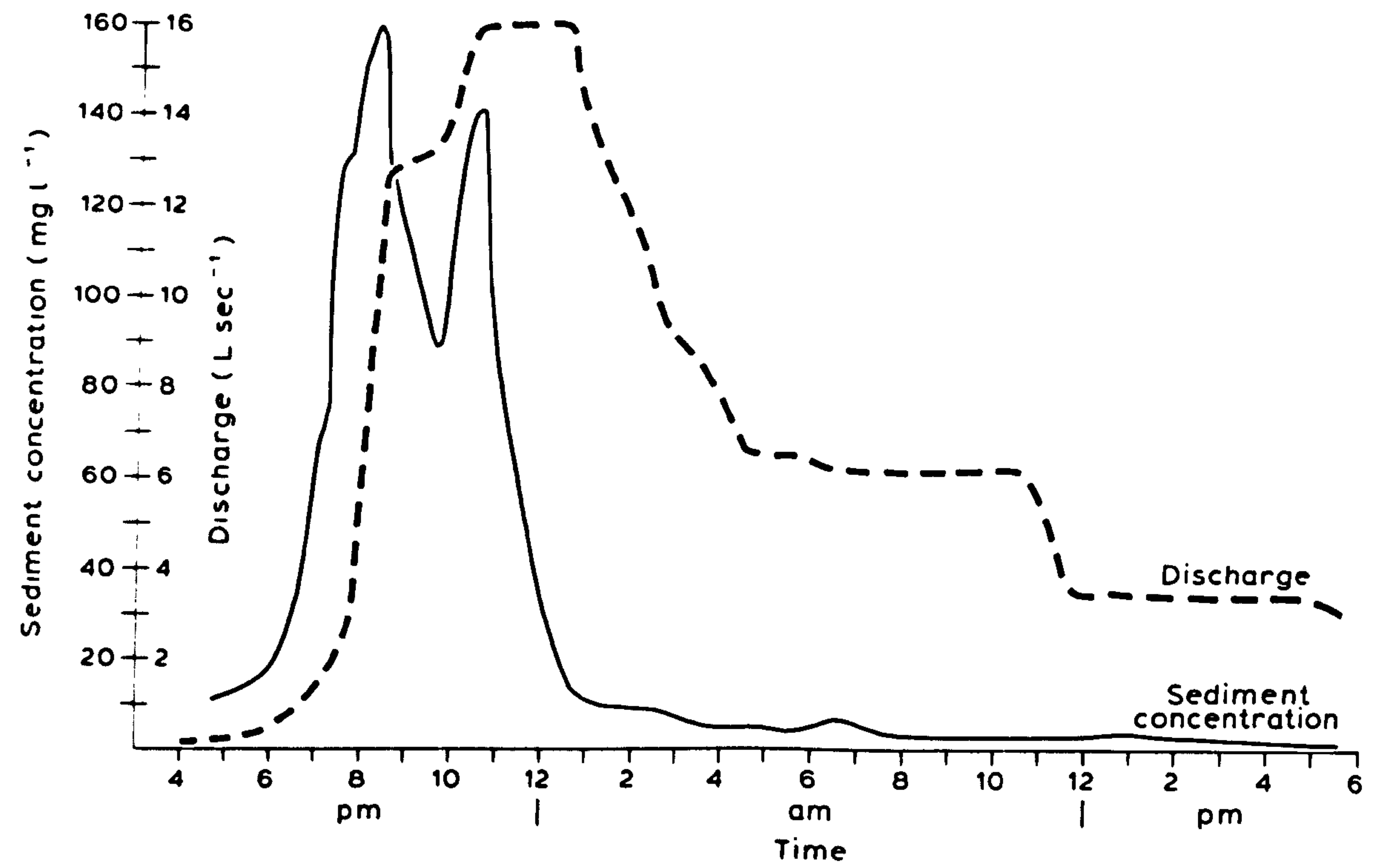


Fig. 17 (a) Water and sediment discharge May 5 to May 6, 1978.

Fig. 17 (b) Hysteresis loop for flood May 5 to May 6, 1978.

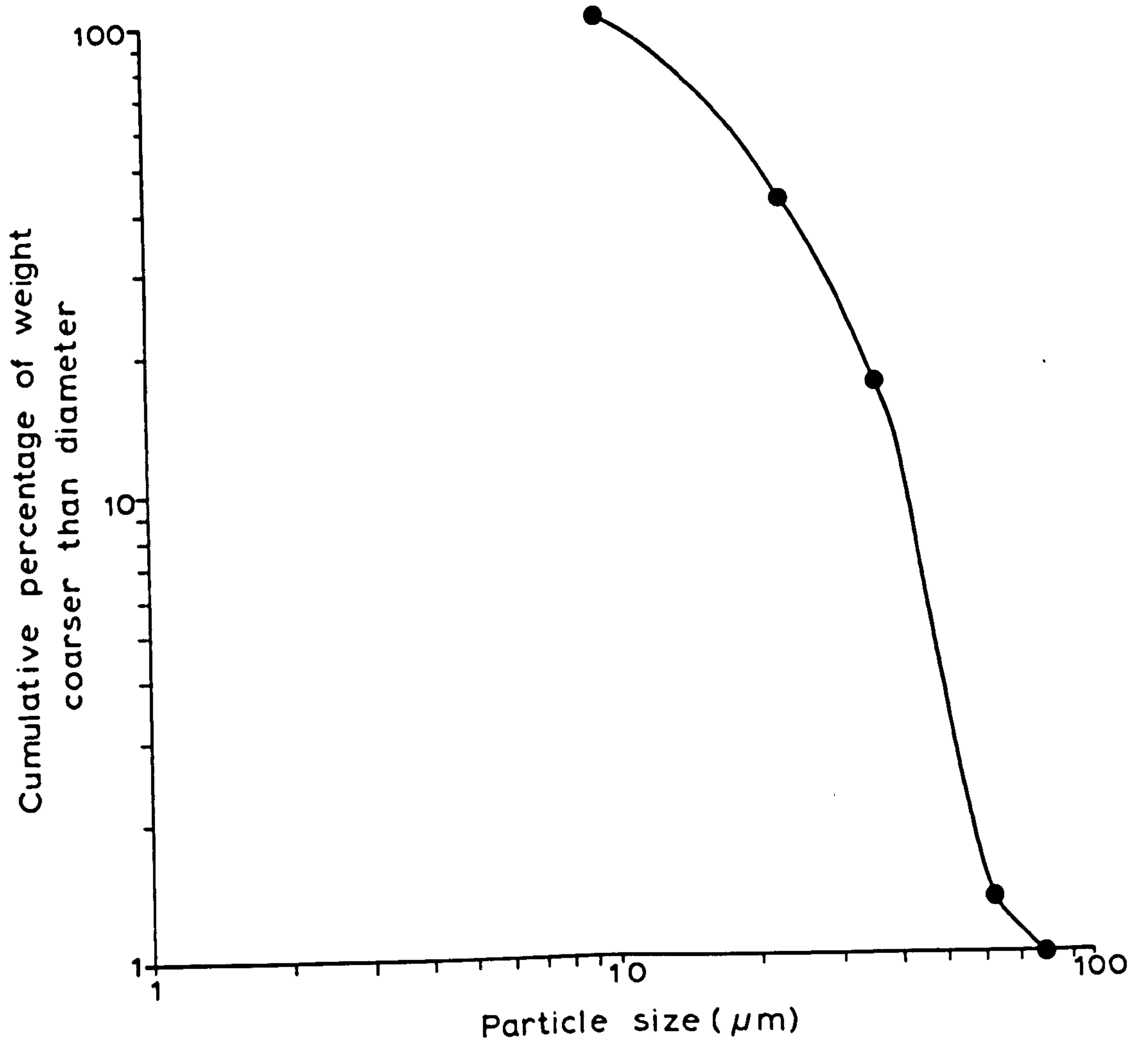


Fig. 18 Mean size distribution of the suspended particles.

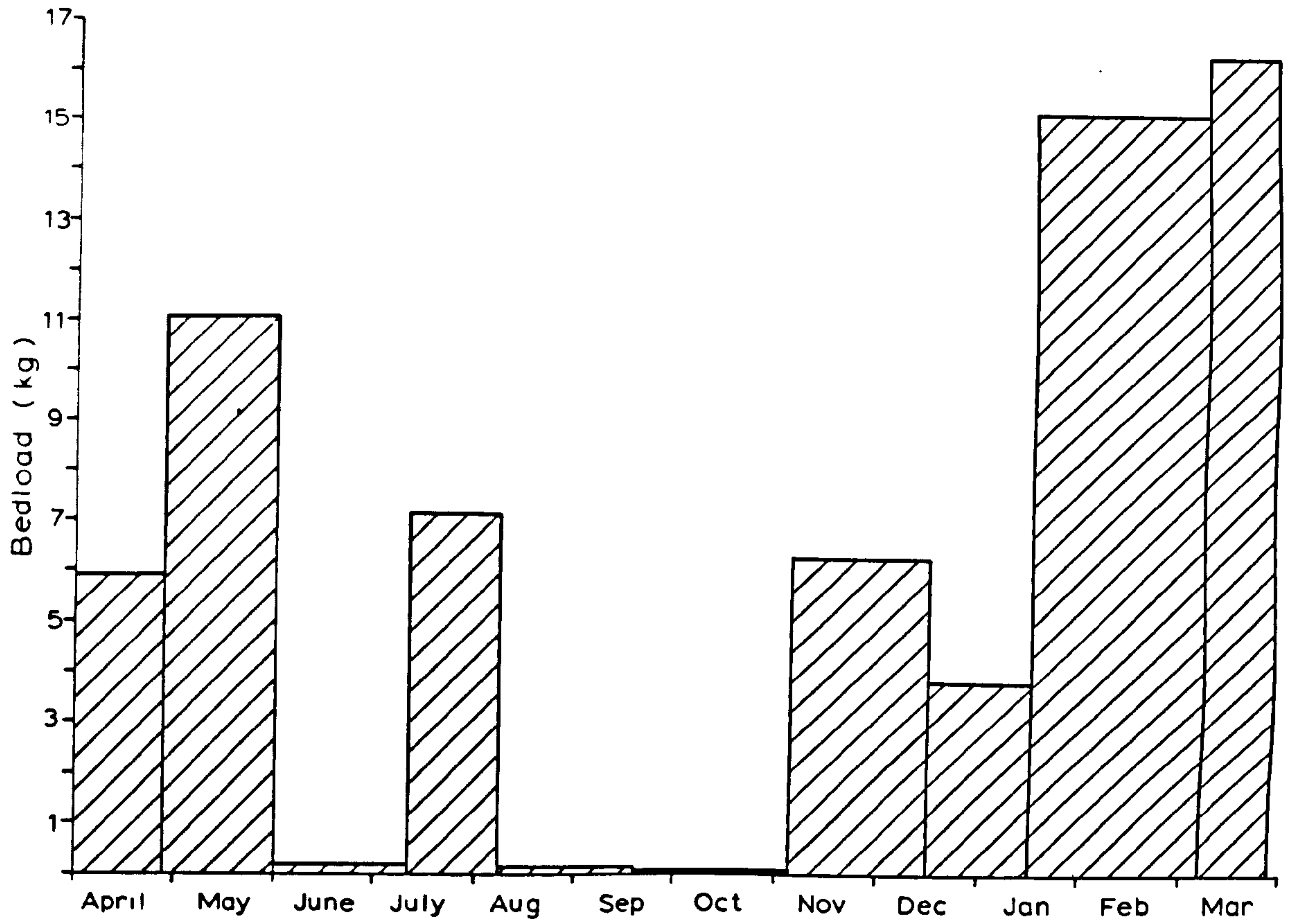


Fig. 19 Bedload transport from Wintergill Catchment.

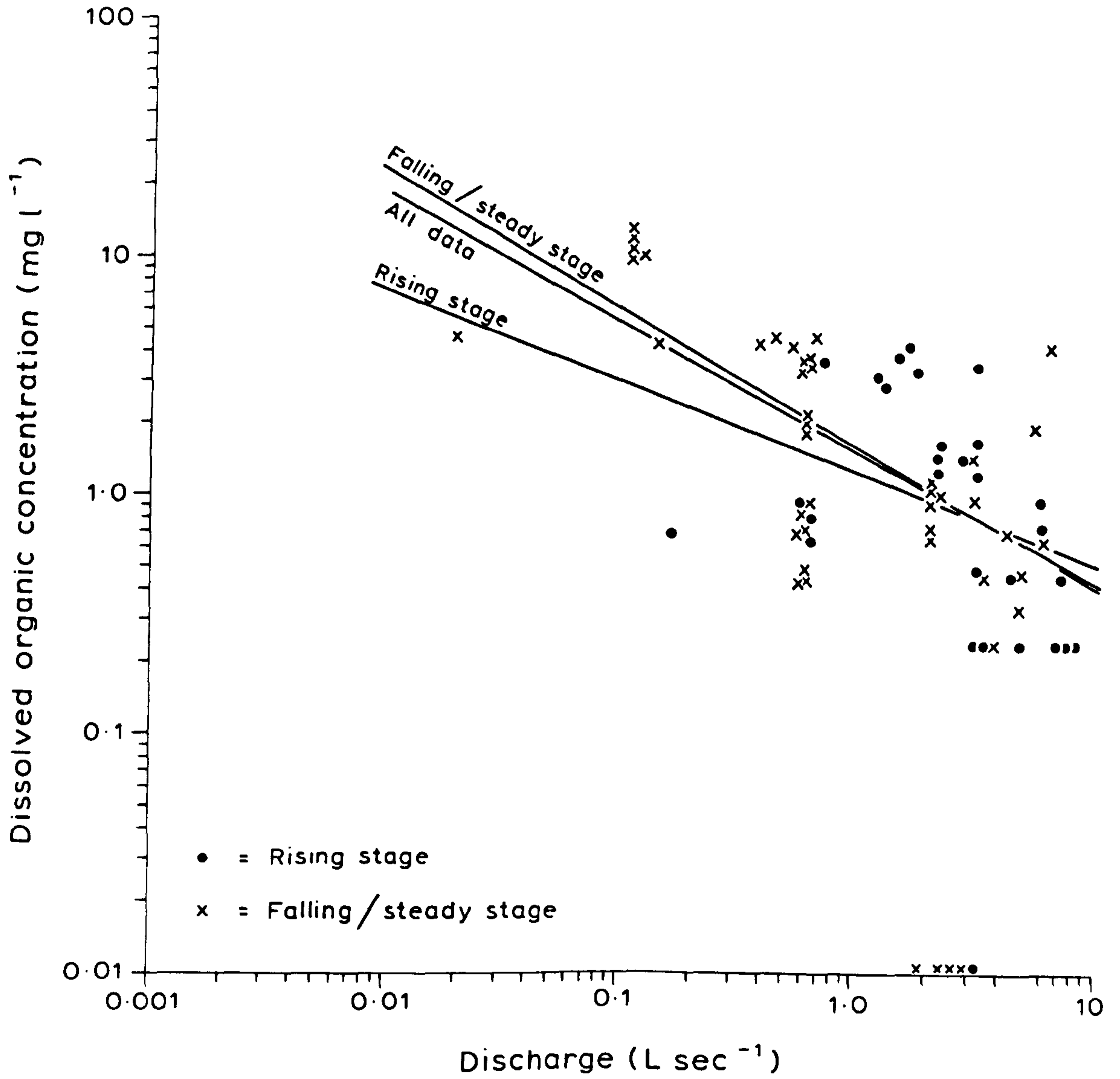


Fig. 20 The relationship between stream discharge (l sec^{-1}) and dissolved organic sediments (mg l^{-1}).

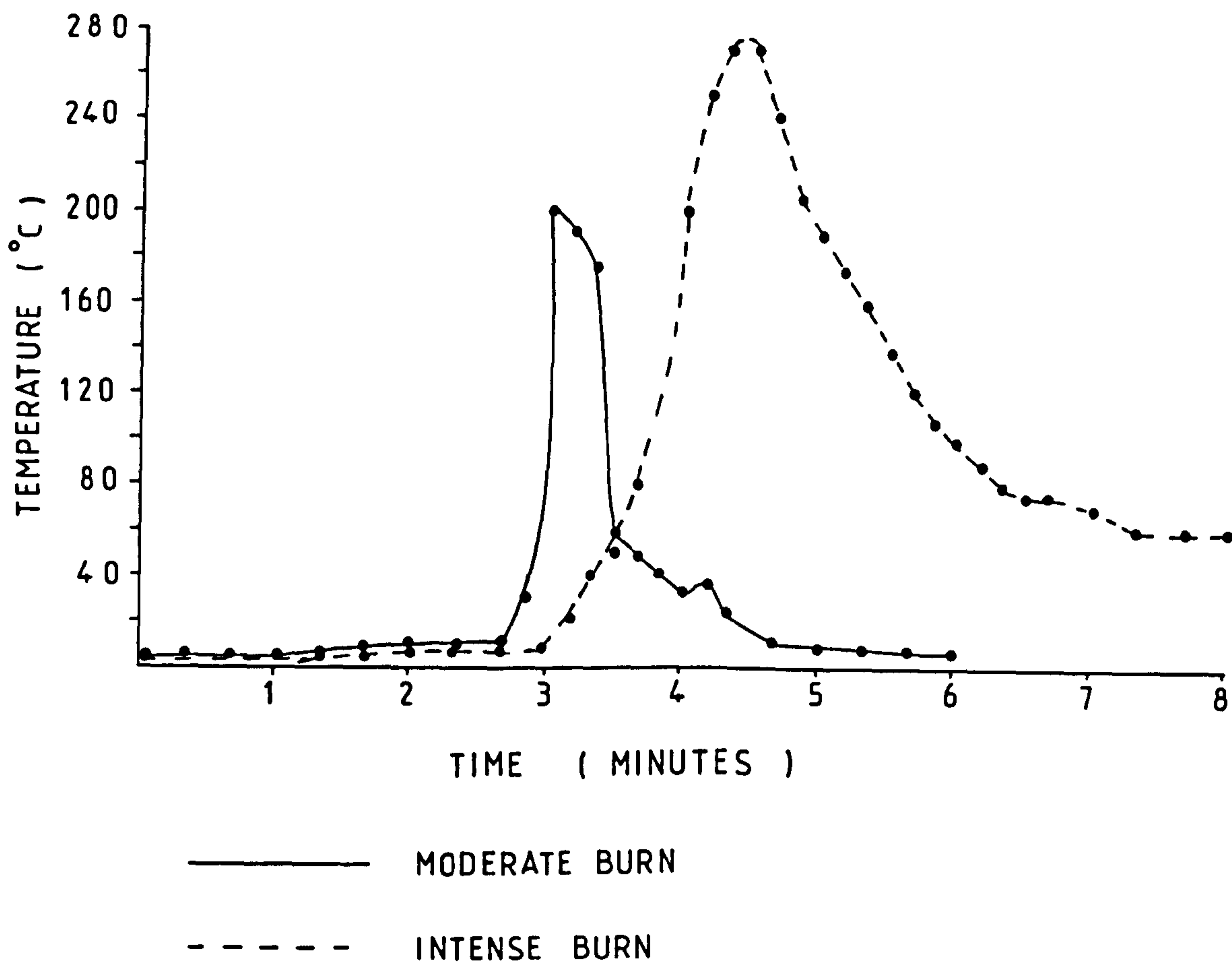


Fig. 21 Temperature changes recorded by the pyrometer during the *muirburns*.

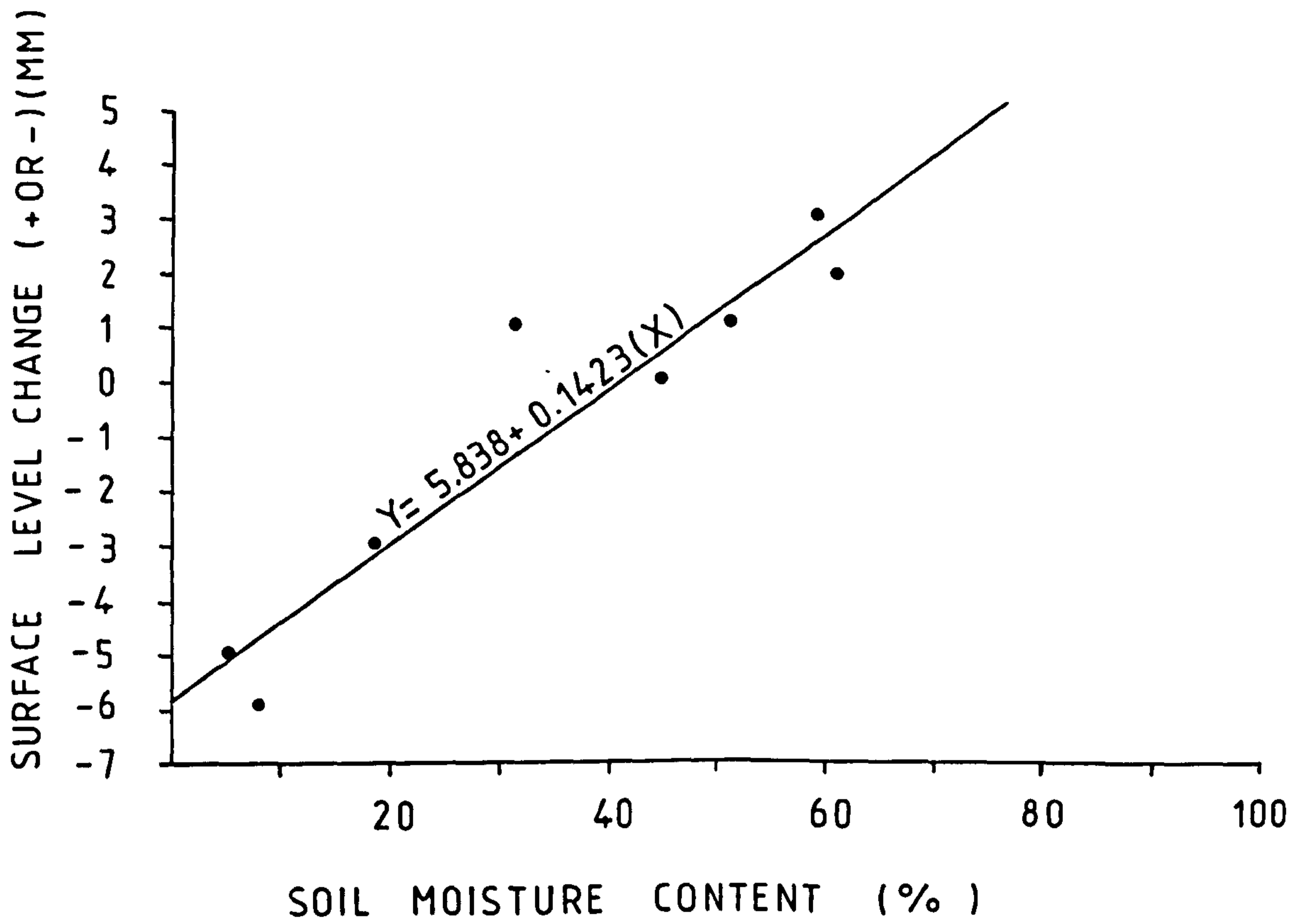


Fig. 22 Relationship between soil moisture content and surface level change of Cladonia (cf Cossifera) lichen.

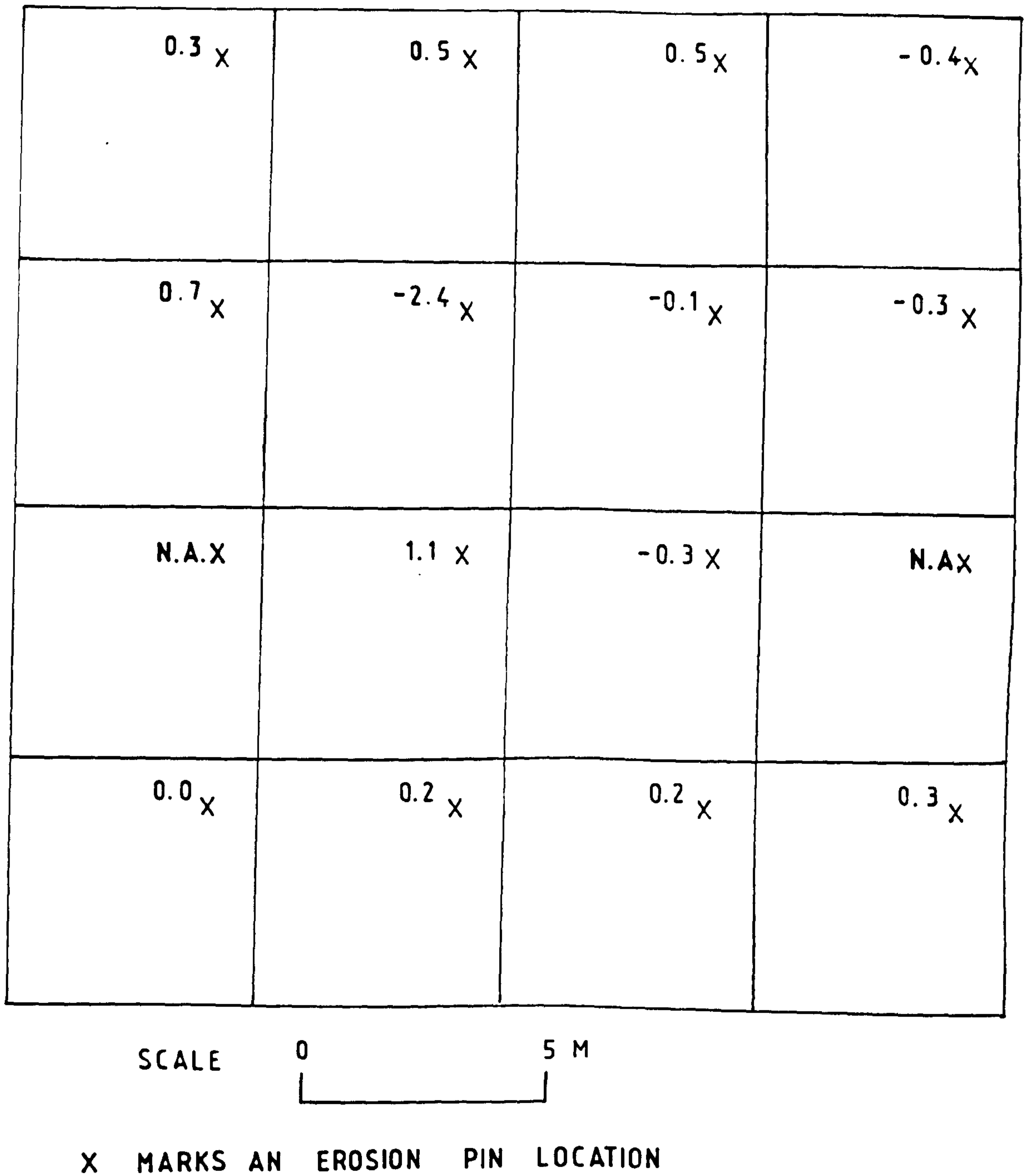


Fig. 23 Surface level changes recorded on the control plot (cm).

OVERLEAF.

Fig. 24 (a) Surface level changes recorded on the moderately burnt plot (cm).

Fig. 24 (b) Surface level changes recorded on the intensively burnt plot (cm).

MODERATELY BURNT PLOT

-0.3 x	-0.3 x	-0.9 x	-0.4 x
0.0 x	-0.6 x	-0.2 x	N. A. x
-0.2 x	-0.6 x	-0.8 x	-0.2 x
0.3 x	0.0 x	-0.8 x	0.1 x

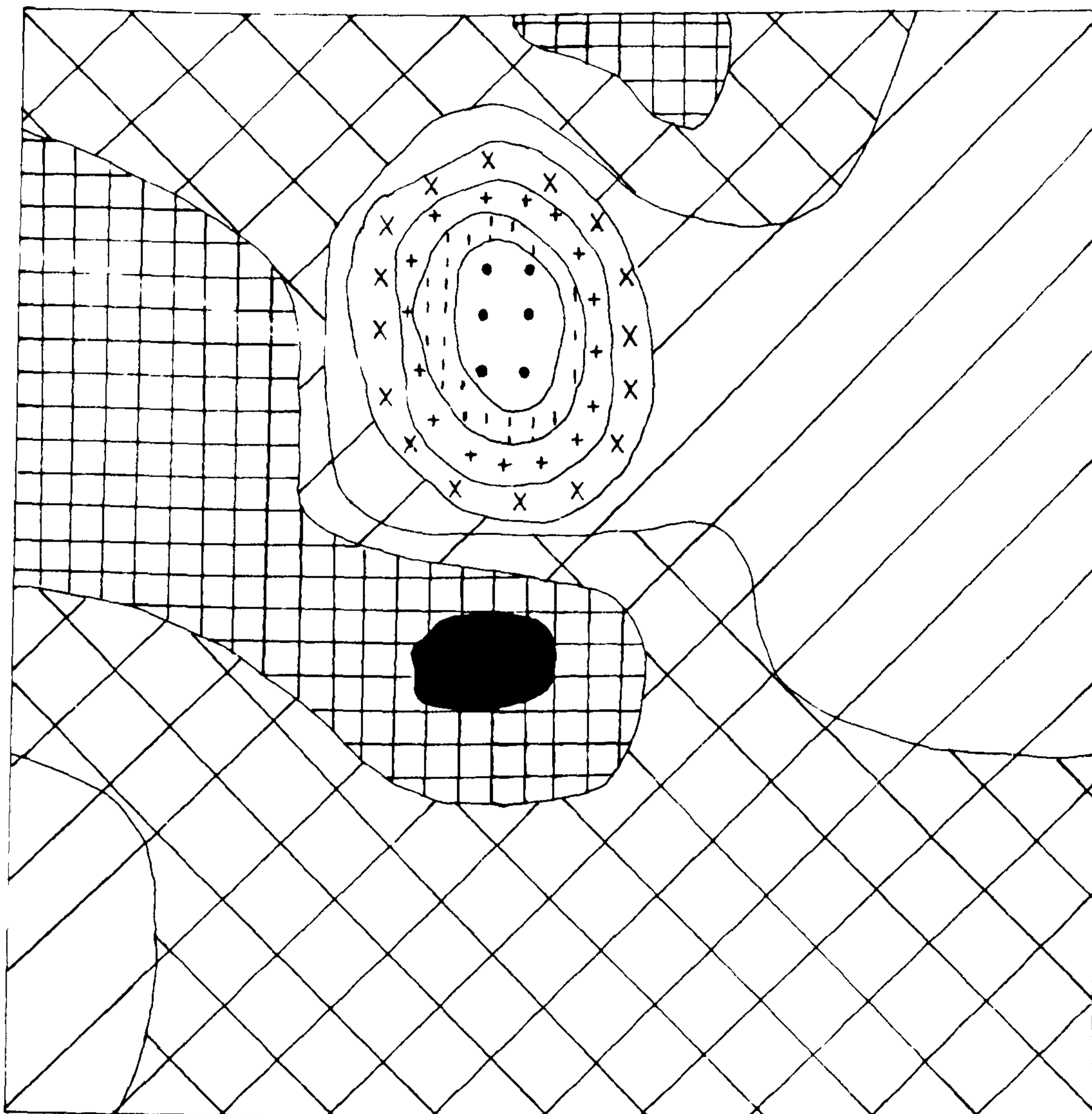
INTENSIVELY BURNT PLOT

-0.1 x	-0.6 x	-1.1 x	-1.3 x
0.0 x	-0.5 x	-0.1 x	0.6 x
-1.2 x	-0.8 x	-0.9 x	0.6 x
-0.6 x	-0.2 x	0.6 x	-0.6 x

SCALE 0 5 M

X MARKS AN EROSION PIN LOCATION

CONTROL PLOT



KEY (CM)


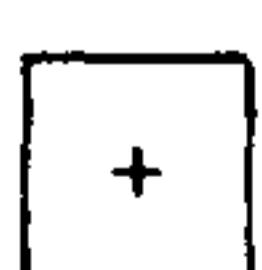

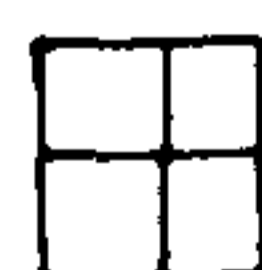
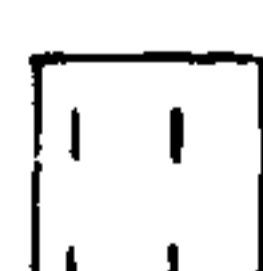
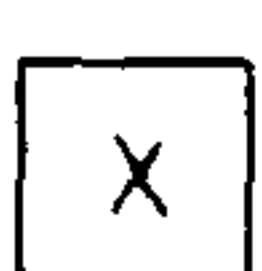


 - 2.5 - 2.0	 - 1.5 - 1.0	 - 0.5 0.0	 0.5 1.0
 - 2.0 - 1.5	 - 1.0 - 0.5	 0.0 0.5	 1.0 1.5

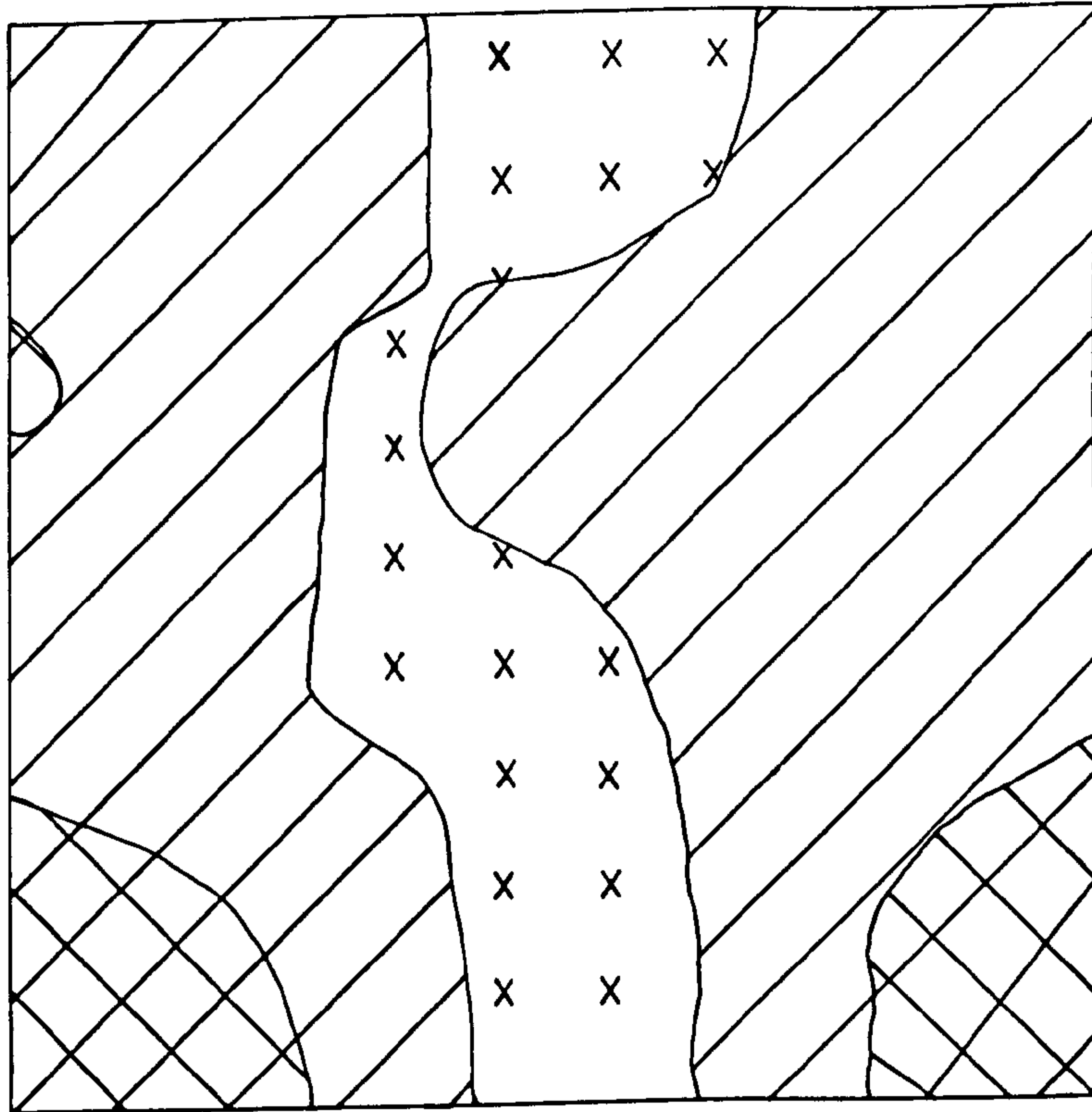
Fig. 25 Contour map of surface level changes recorded on the control plot.

OVERLEAF.

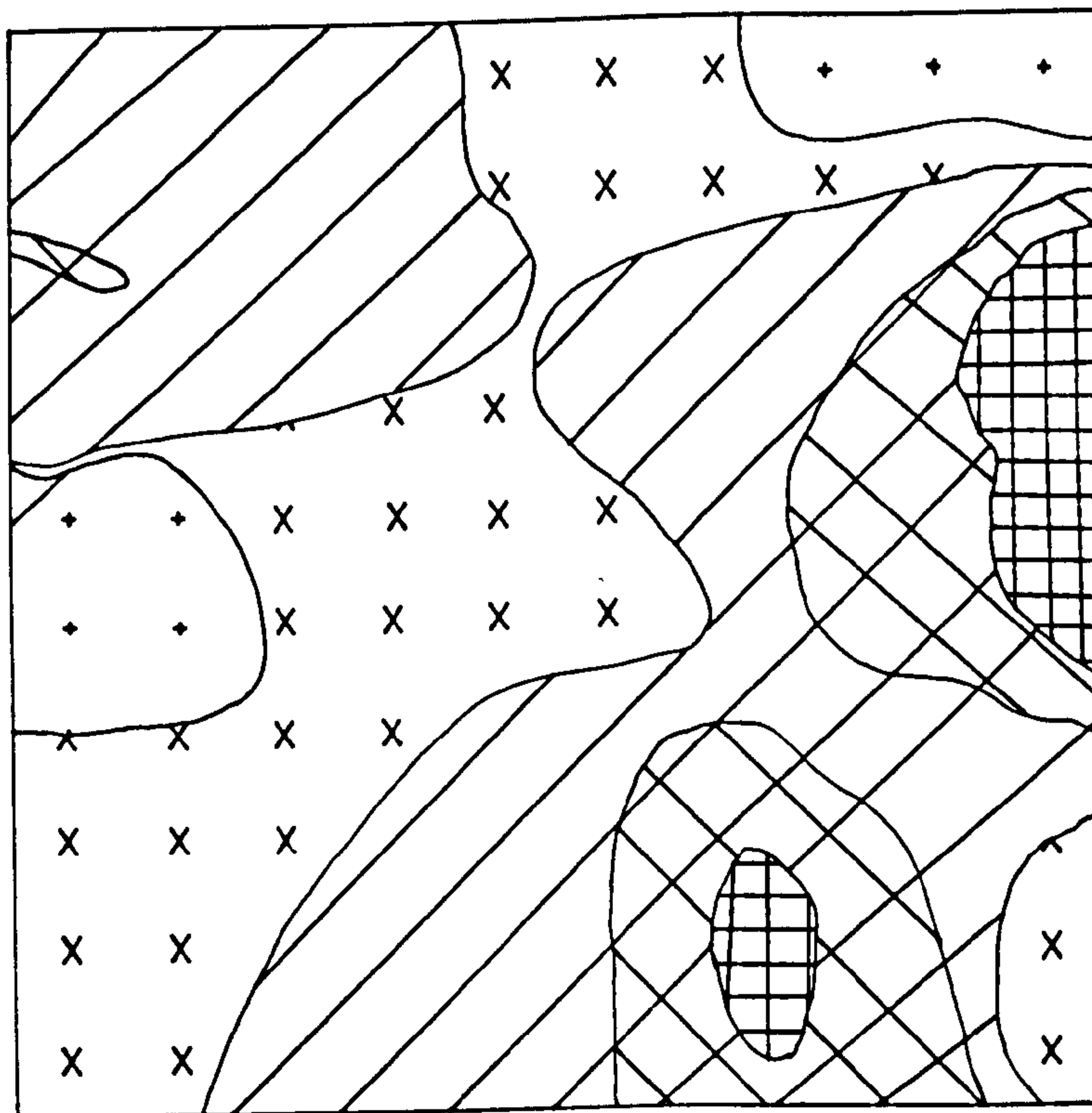
Fig. 26 (a) Contour map of surface level changes recorded on the moderately burnt plot.

Fig. 26 (b) Contour map of surface level changes recorded on the intensively burnt plot.





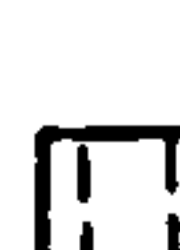











MODERATELY BURNT PLOT



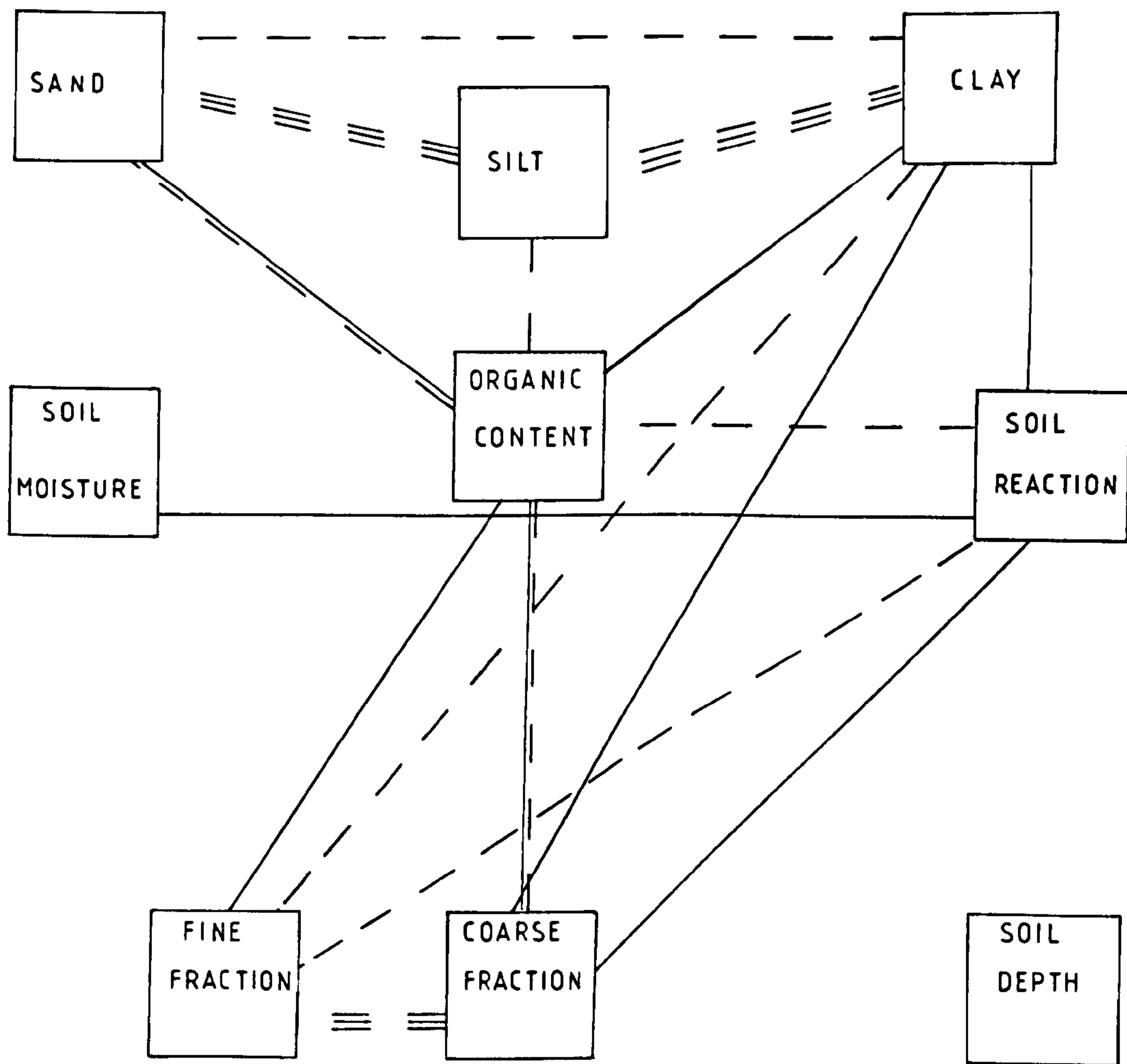
INTENSIVELY BURNT PLOT



KEY (CM)

 -2.5	 -1.5	 -0.5	 0.5
 -2.0	 -1.0	 0.0	 1.0
 -2.0	 -1.0	 0.0	 1.0
 -1.5	 -0.5	 0.5	 1.5

CORRELATION MATRIX OF THE SOIL VARIABLES.



_____ SIG. 0.05 LEVEL
 ===== SIG. 0.01 LEVEL
 ===== SIG. 0.001 LEVEL

_____ POSITIVE CORRELATION
 - - - - - NEGATIVE CORRELATION
 ===== REVERSIBLE CORRELATION

Fig. 27 Correlation matrix of the soil properties.

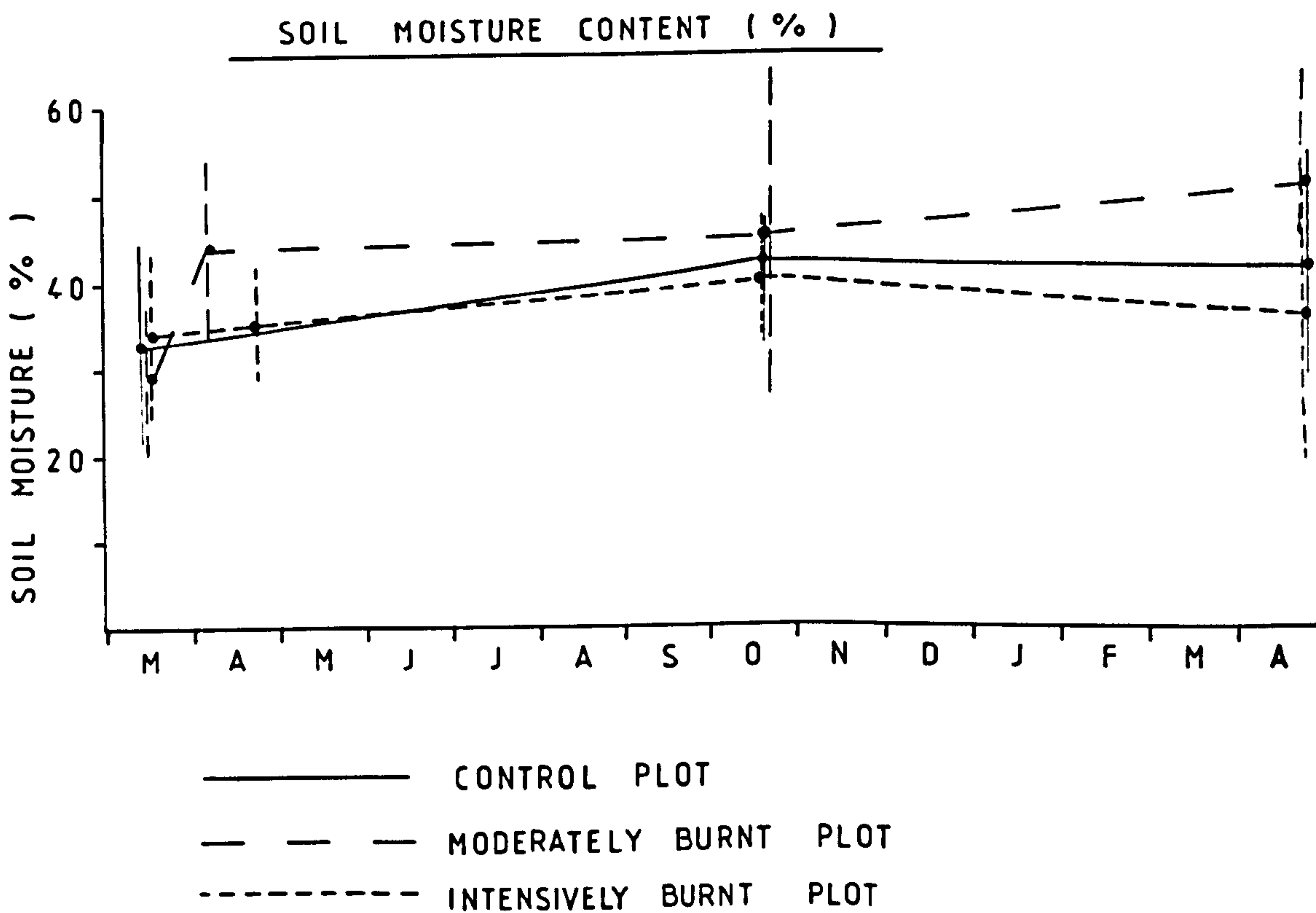
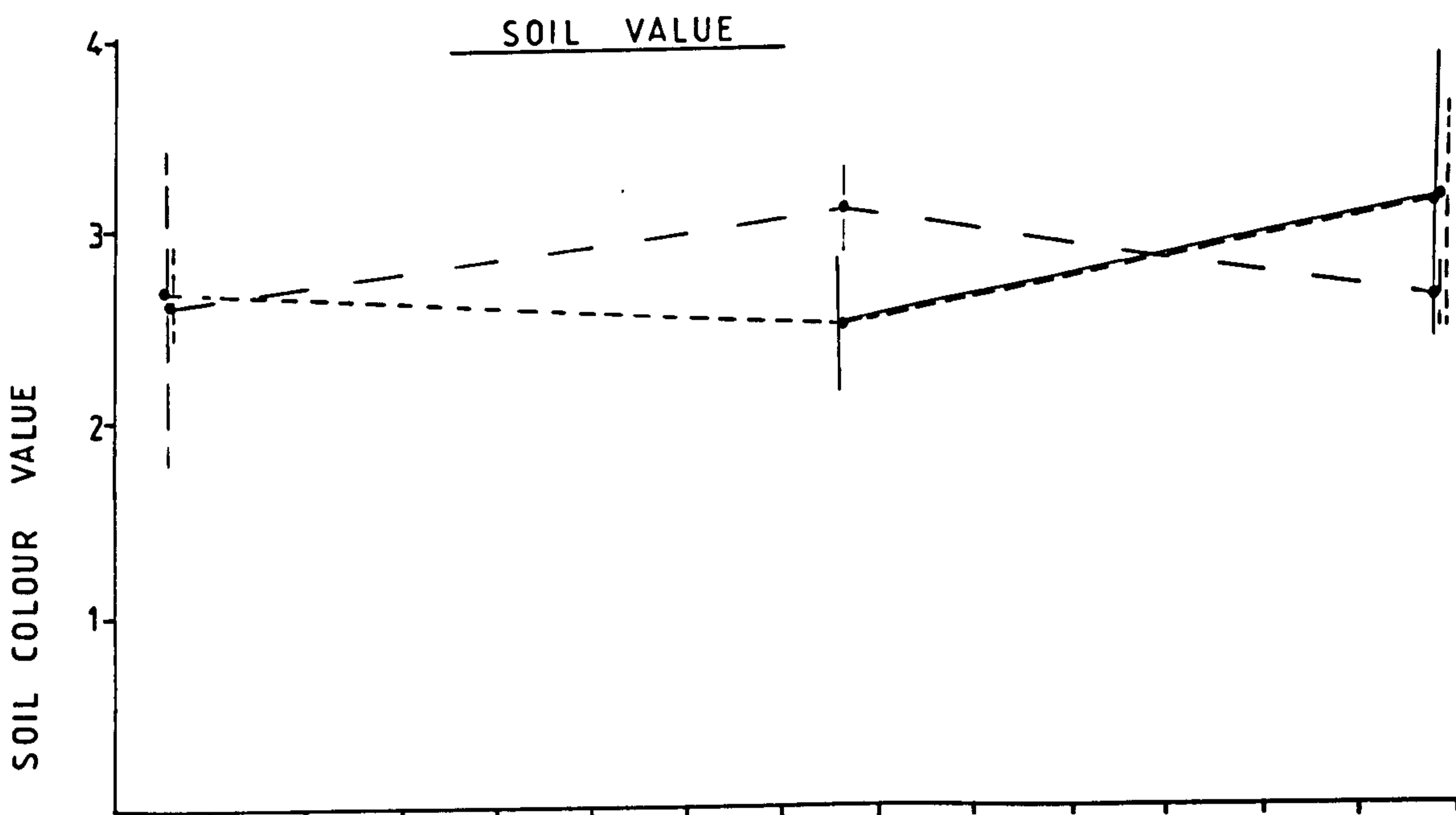


Fig. 28 (a) Changes in mean soil colour values within the Egton High Moor plots (including standard deviations).

Fig. 28 (b) Changes in mean soil moisture contents within the Egton High Moor plots (including standard deviations).

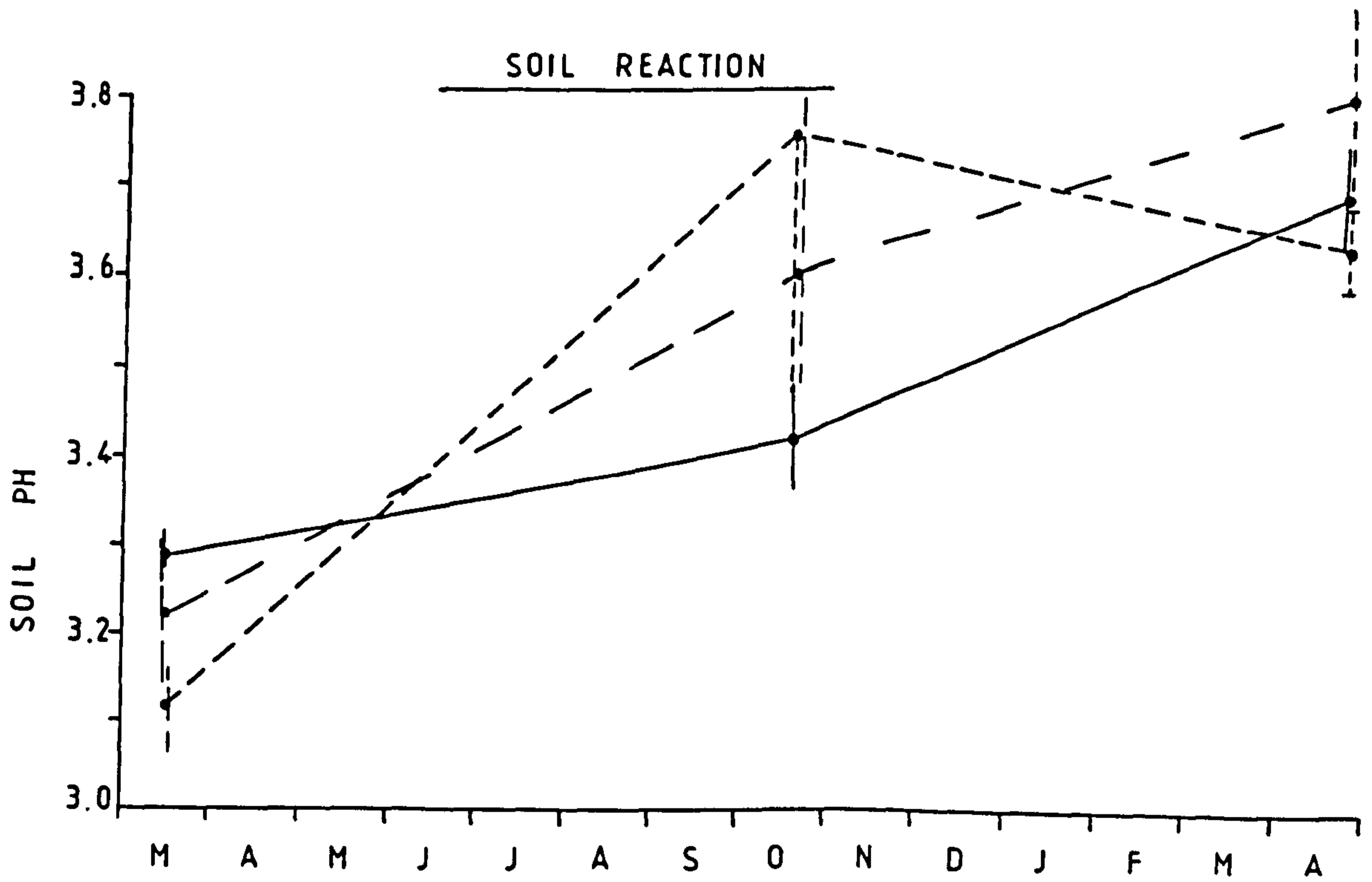
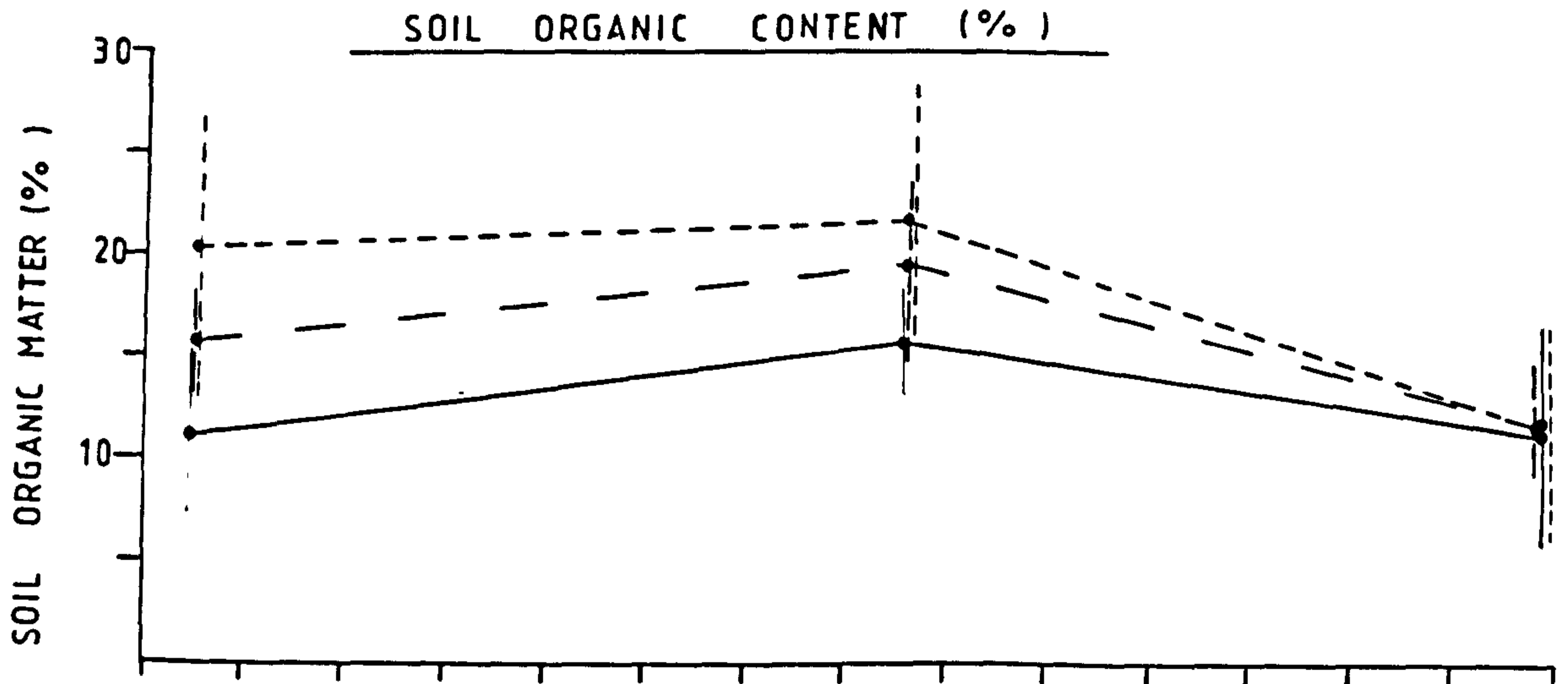


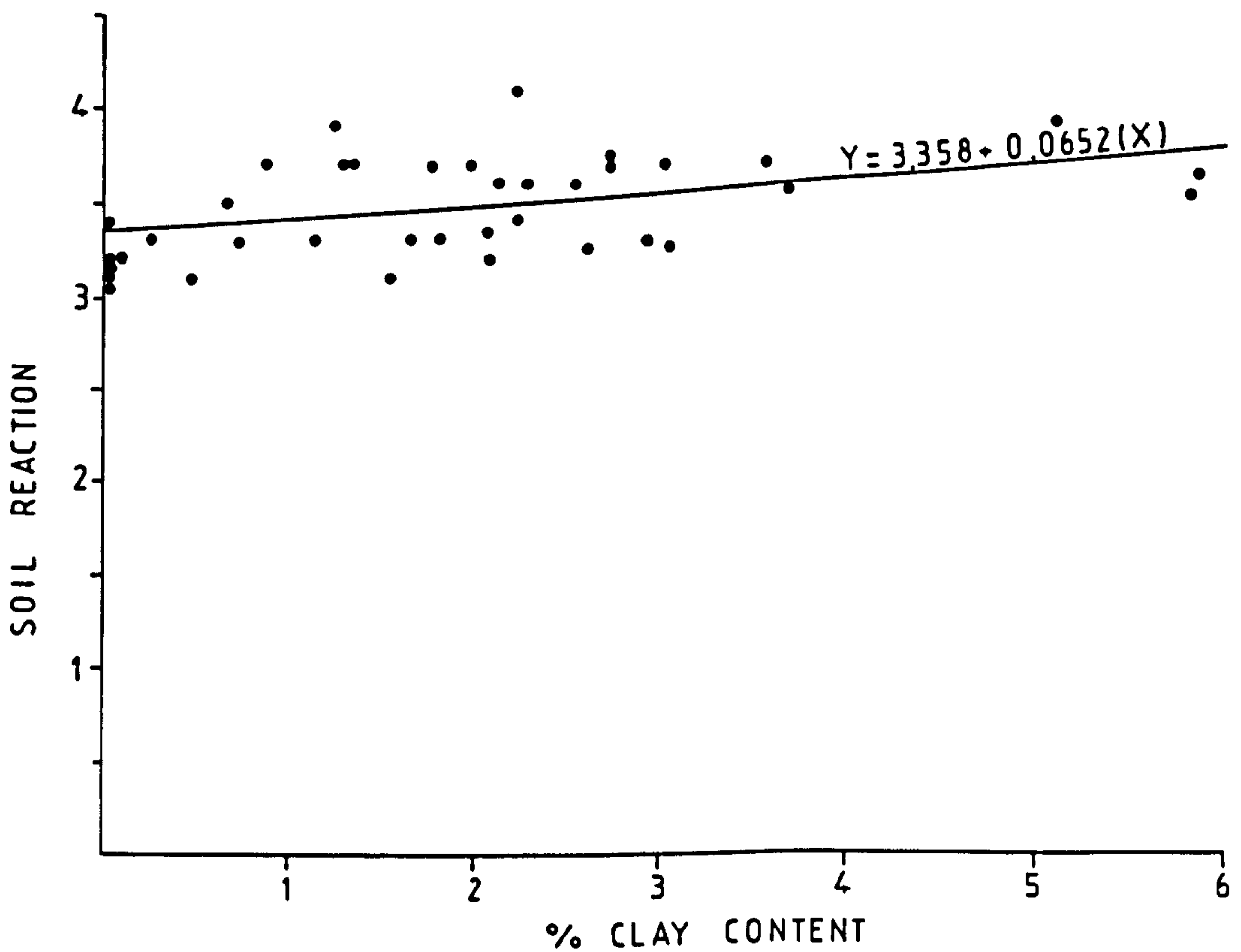
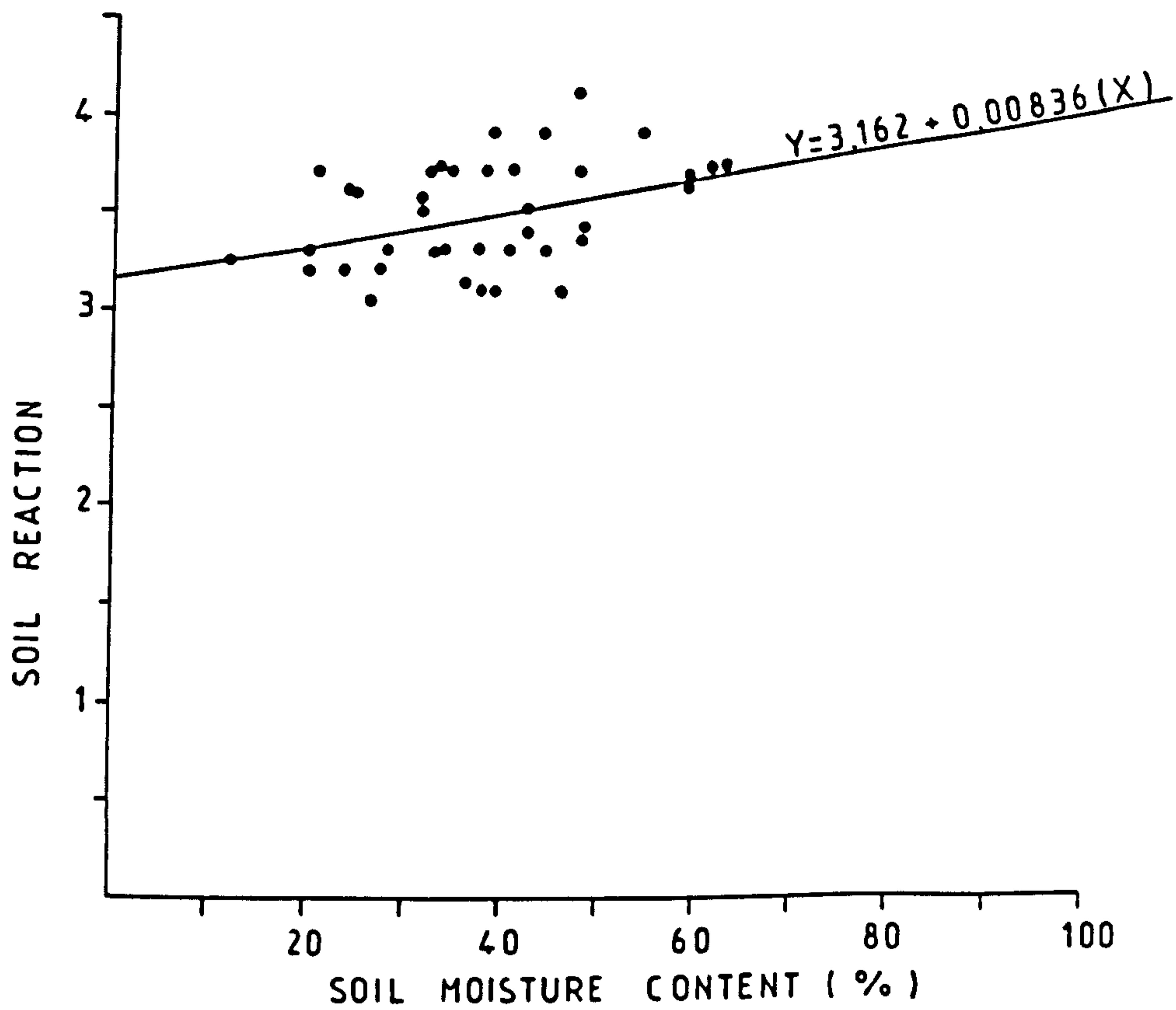
Fig. 29 (a) Changes in mean soil organic contents within the Egton High Moor plots (including standard deviations).

Fig. 29 (b) Changes in mean soil reactions within the Egton High Moor plots (including standard deviations).

OVERLEAF.

Fig. 30 (a) The relationship between soil moisture content and pH
within the Egton High Moor plots.

Fig. 30 (b) The relationship between clay content and pH within
the Egton High Moor plots.



TENTATIVE MODEL OF SOIL REACTION

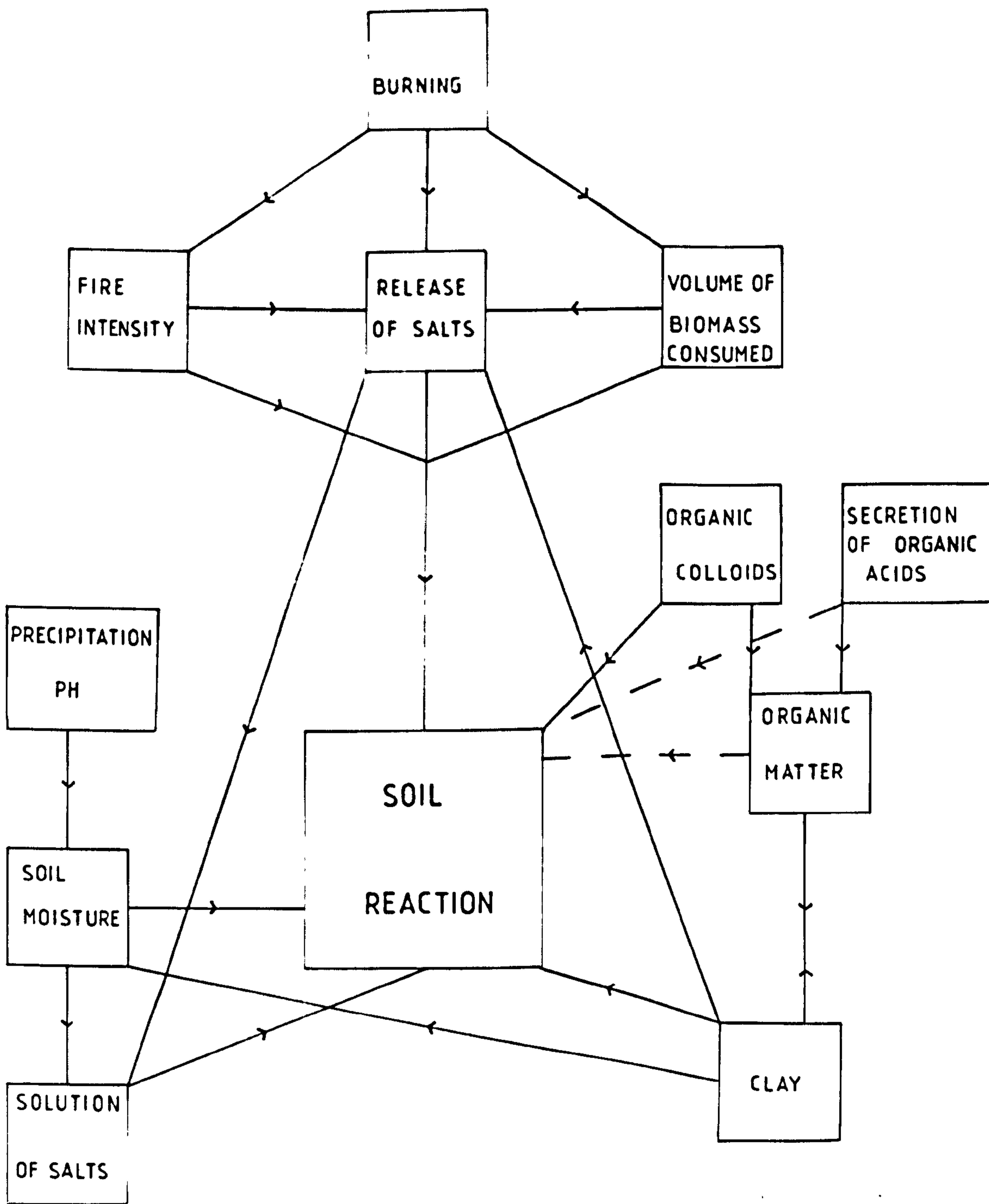


Fig. 31 Tentative model of soil reaction.

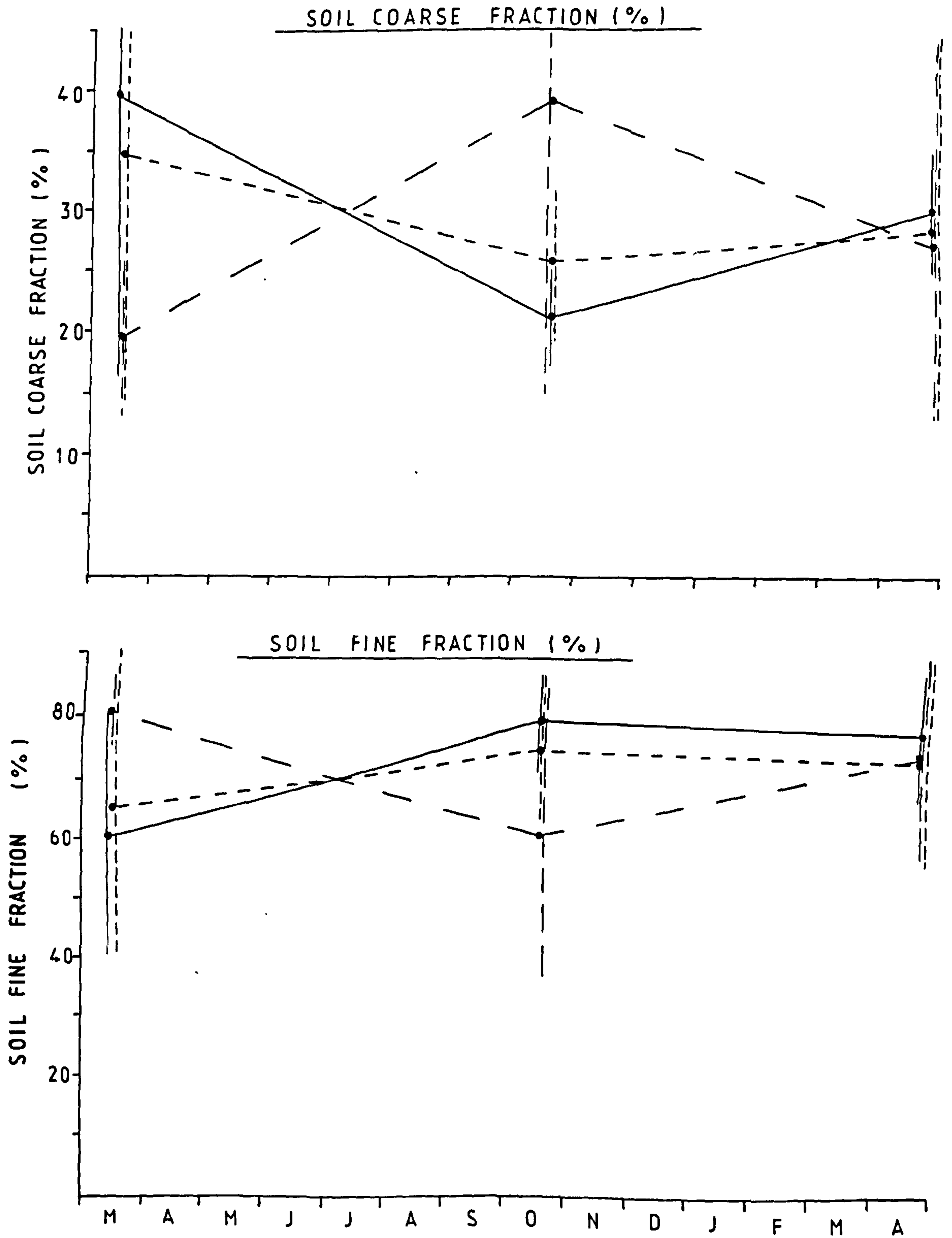


Fig. 32 (a) Changes in mean coarse fraction content within the Egton High Moor plots (including standard deviations).

Fig. 32 (b) Changes in mean fine fraction content within the Egton High Moor plots (including standard deviations).

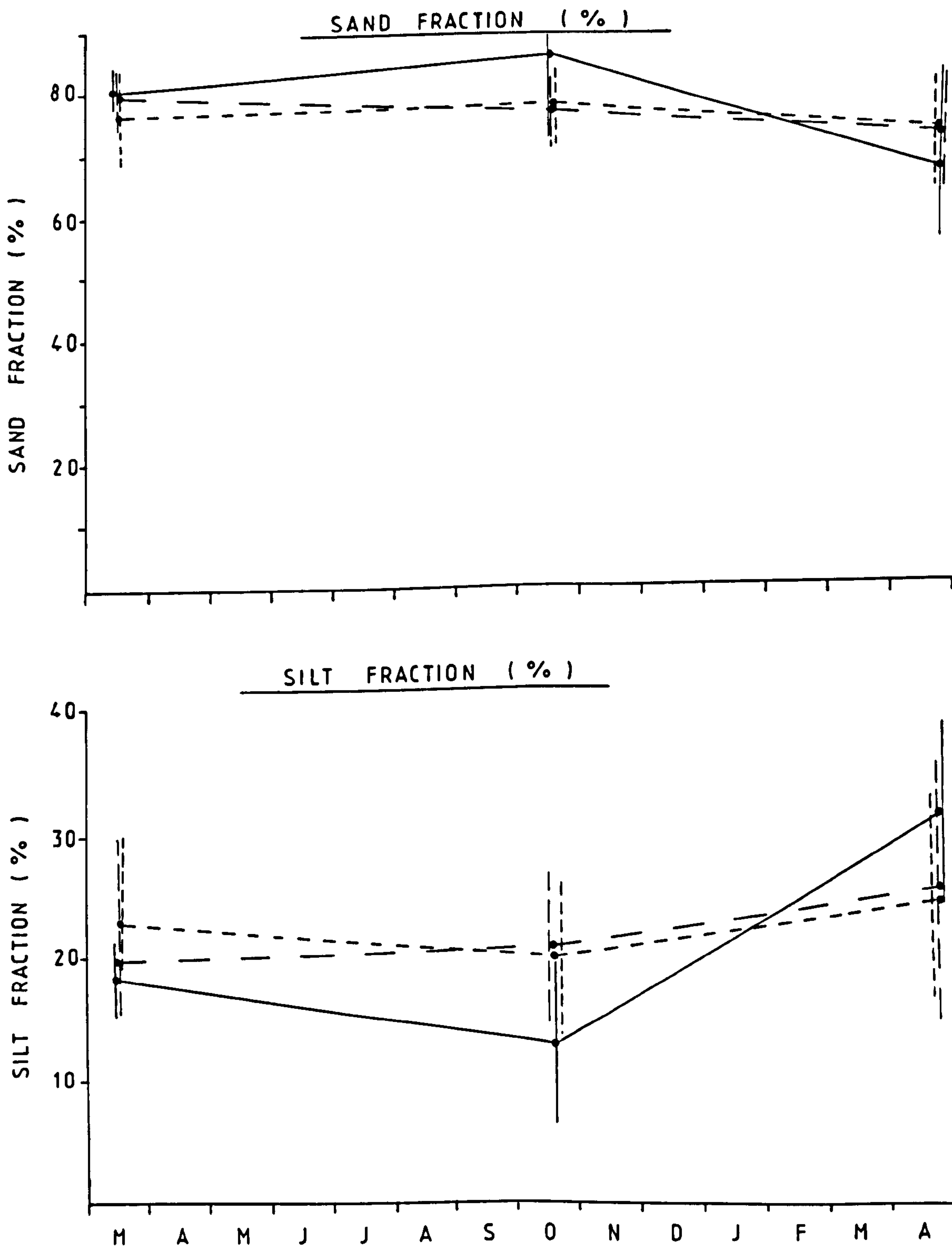


Fig. 33 (a) Changes in mean sand fraction content within the Egton High Moor plots (including standard deviations).

Fig. 33 (b) Changes in mean silt fraction content within the Egton High Moor plots (including standard deviations).

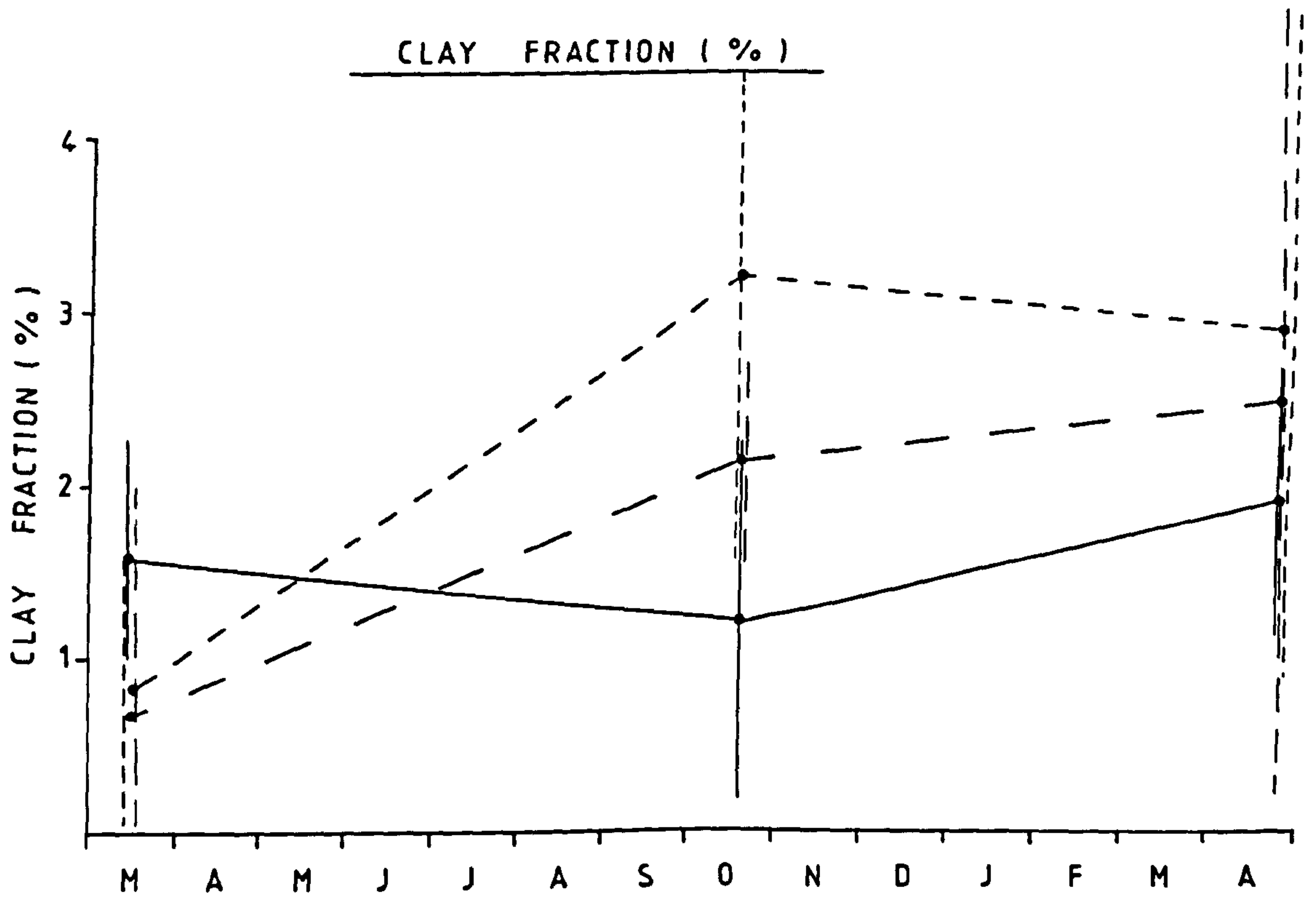
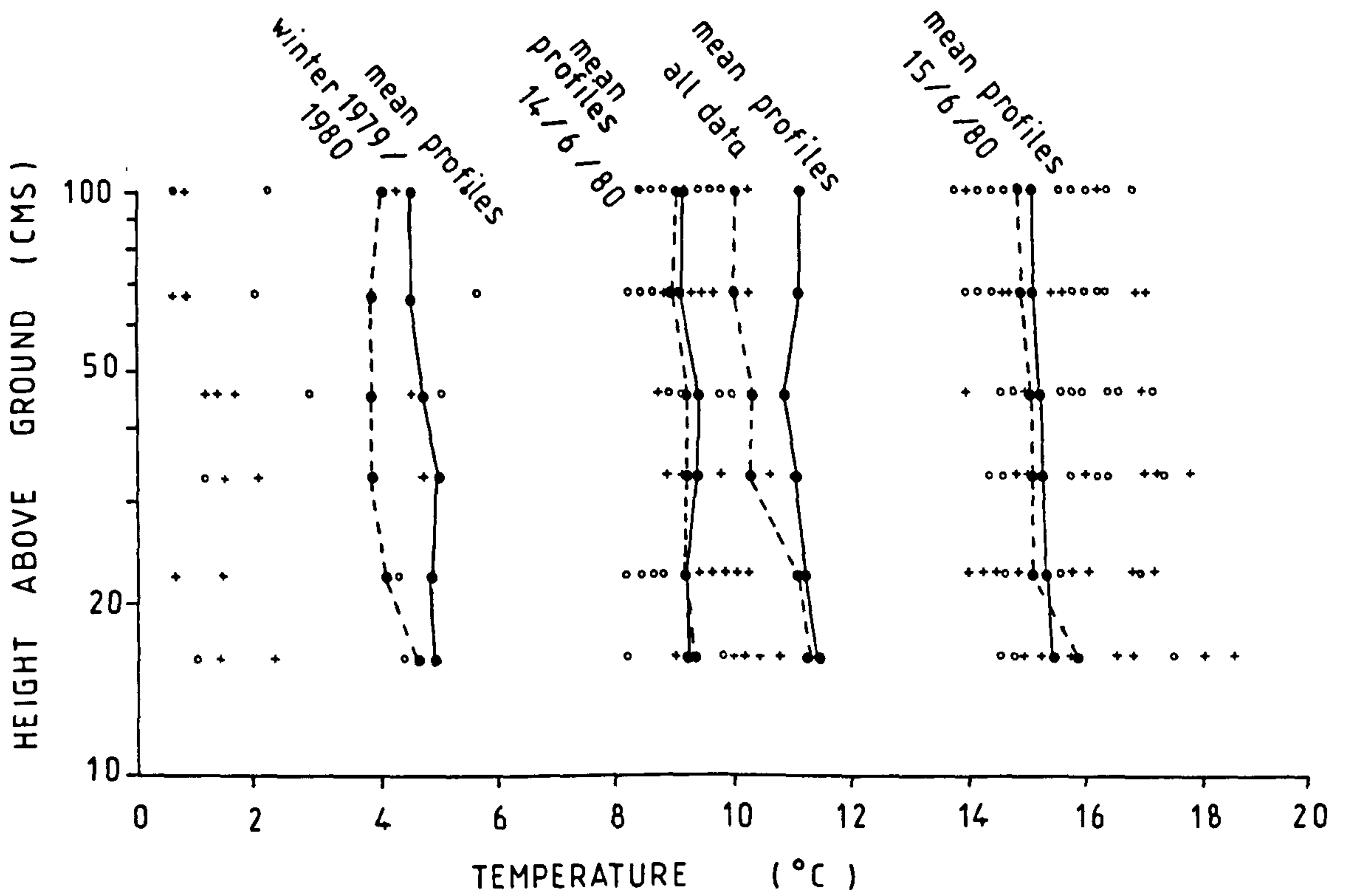


Fig. 34 Changes in mean clay fraction content within the Egton High Moor plots (including standard deviations).



- TEMPERATURE RECORDING ABOVE / WITHIN HEATHER.
- TEMPERATURE RECORDING ABOVE BURNT GROUND.
- TEMPERATURE PROFILE ABOVE / WITHIN HEATHER.
- - - TEMPERATURE PROFILE ABOVE BURNT GROUND.

Fig. 35 Temperature profiles above the burnt and vegetated ground on Egton High Moor.

Temperatures Recorded by the probes June 11 - June 17

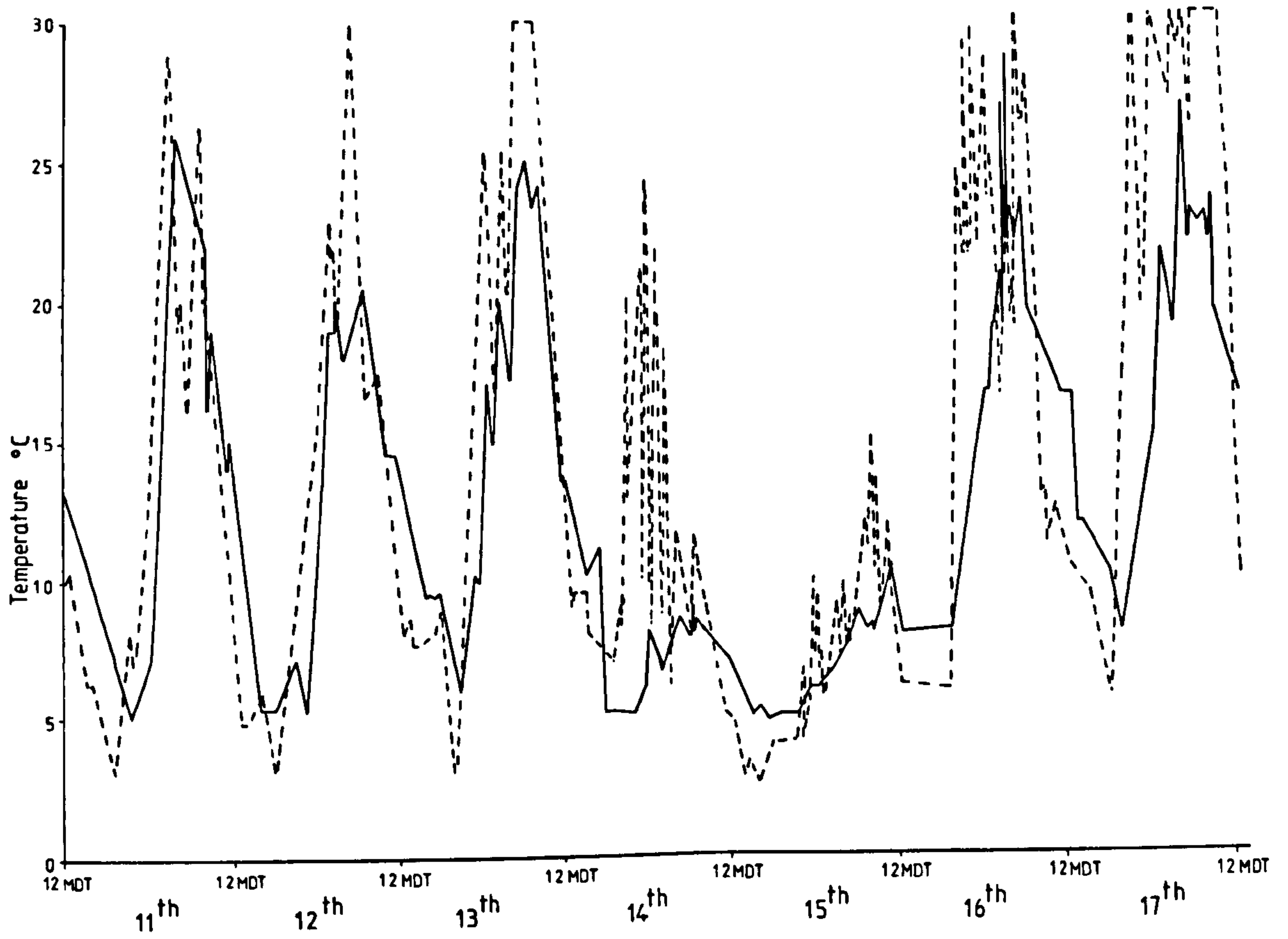


Fig. 36 Temperatures recorded by the two probes, June 11 to June 17, 1979.

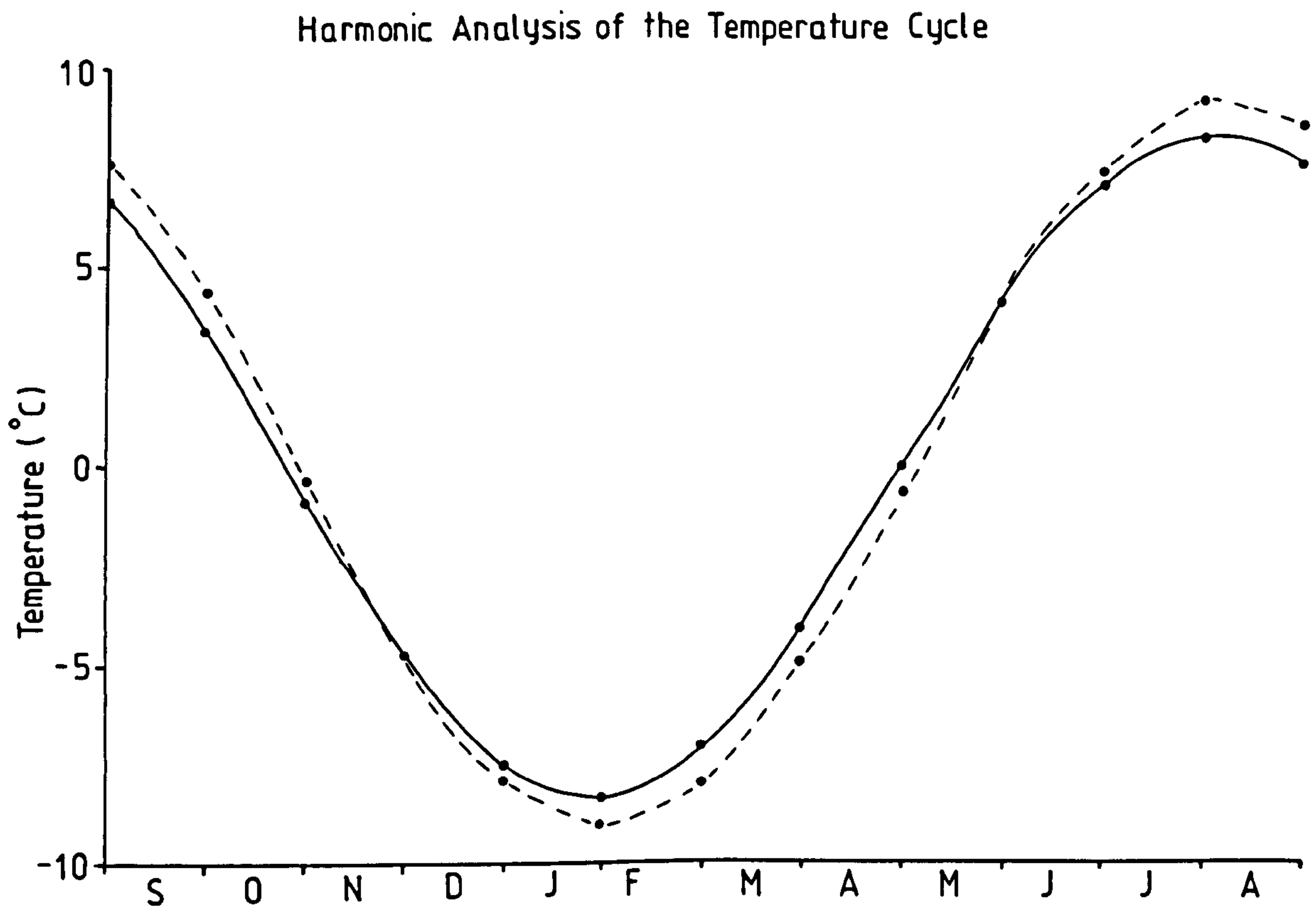
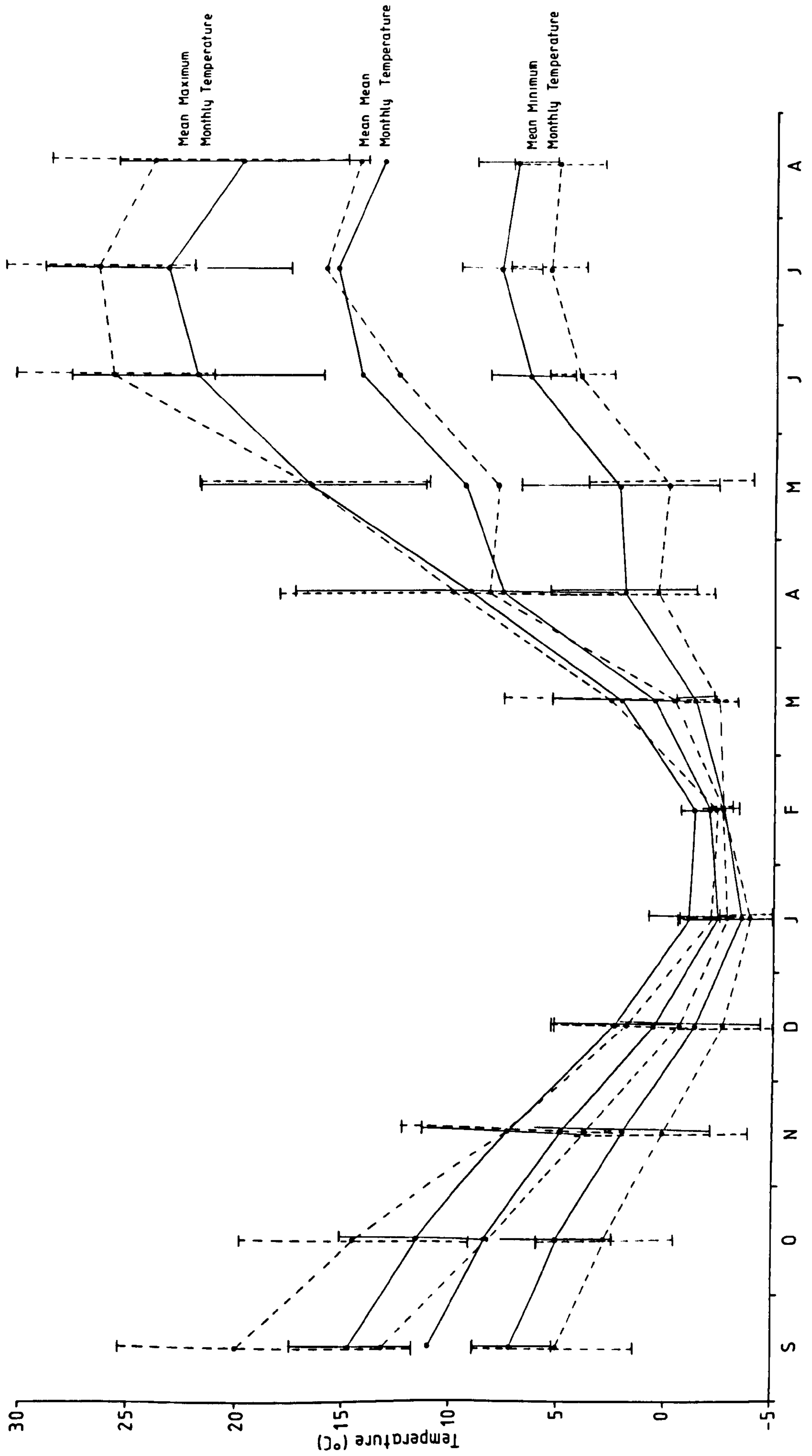


Fig. 37 Harmonic analysis of the annual temperature cycle.

OVERLEAF.

Fig. 38 Mean monthly maximum, mean monthly mean and mean monthly minimum temperatures recorded by the two probes (including standard deviations of mean monthly maximum and mean monthly minimum temperatures).



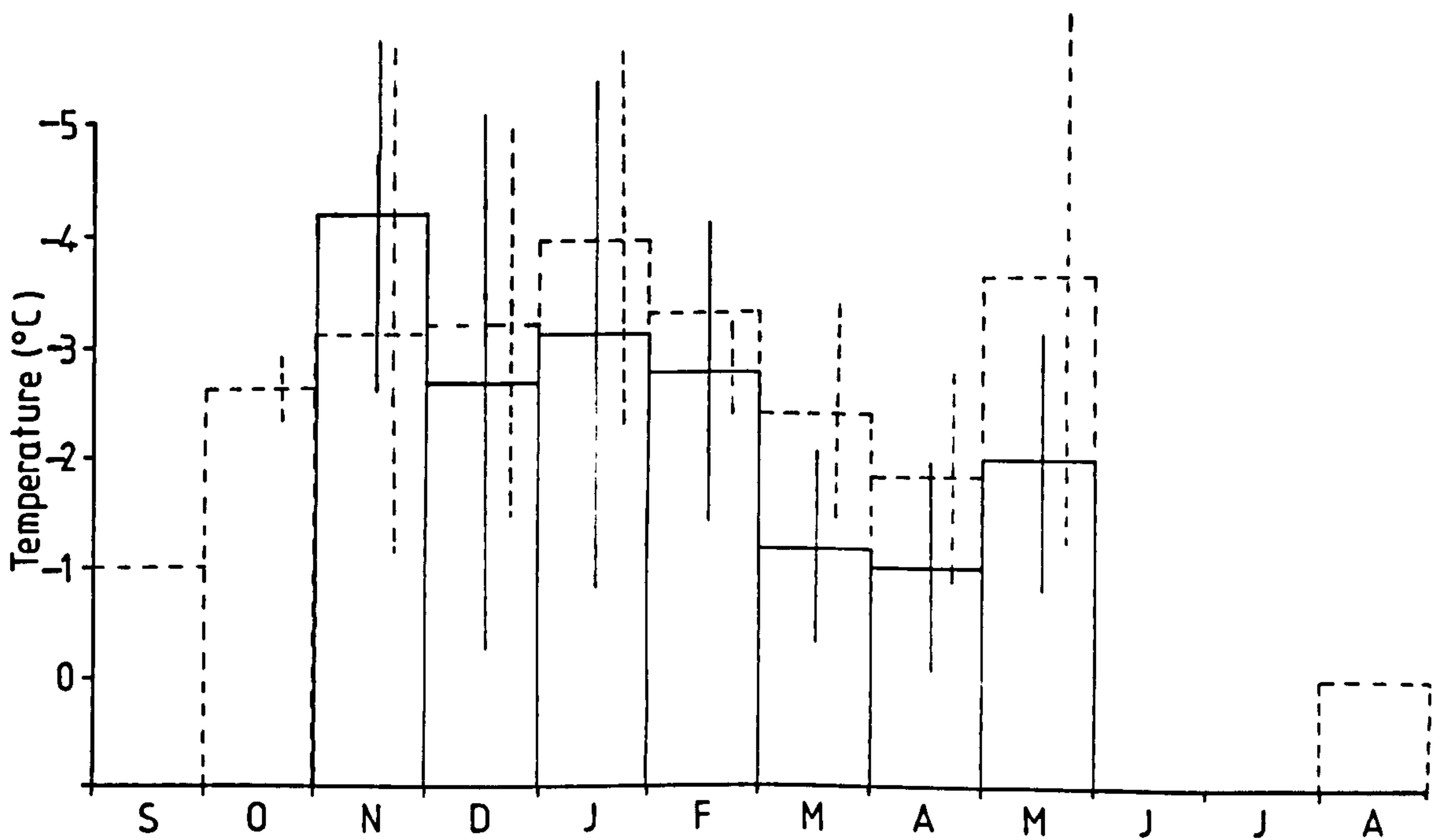
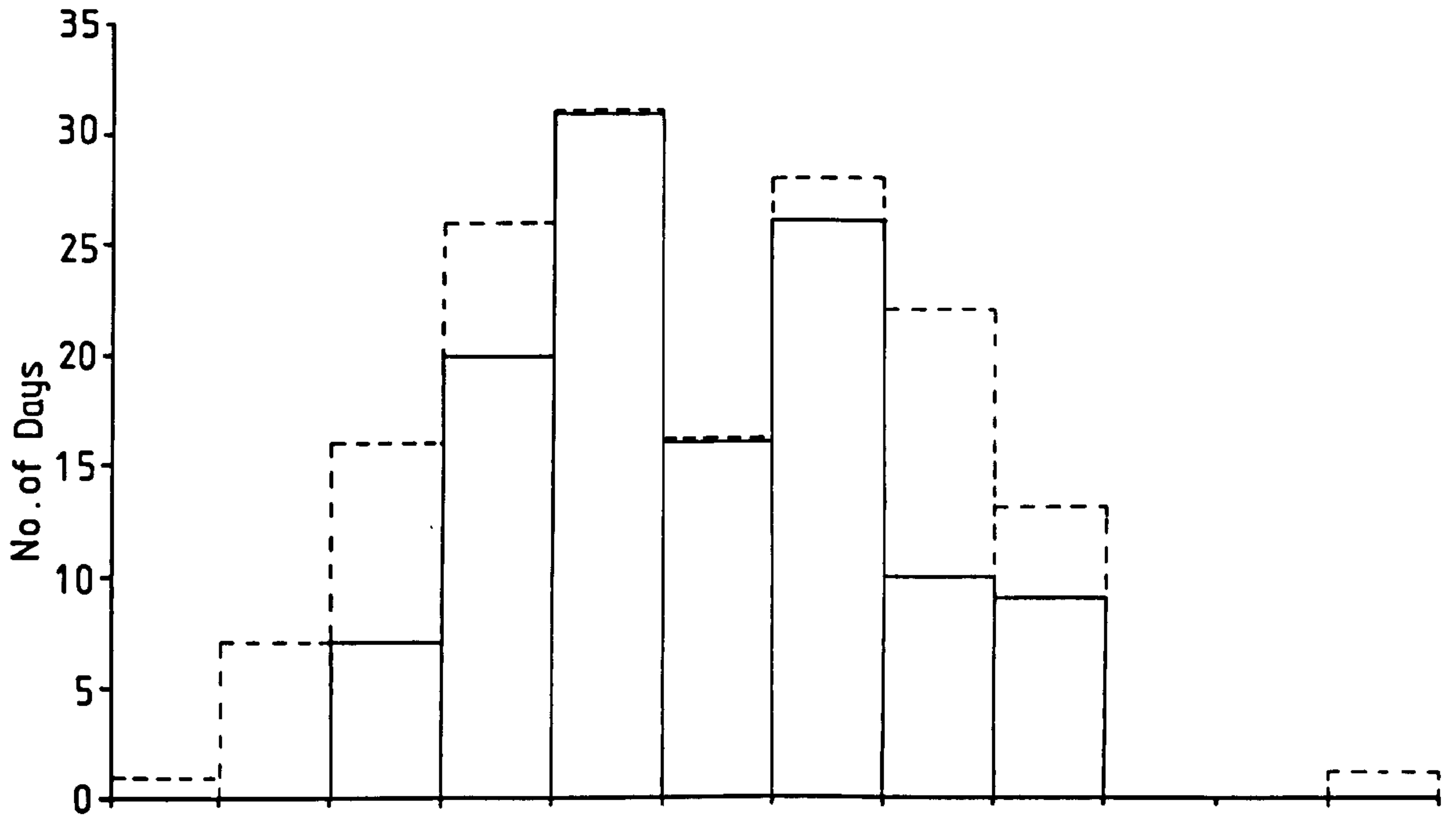


Fig. 39 (a) Number of days on which sub-zero temperatures recorded.

Fig. 39 (b) Mean monthly minimum sub-zero temperatures (including standard deviations) .

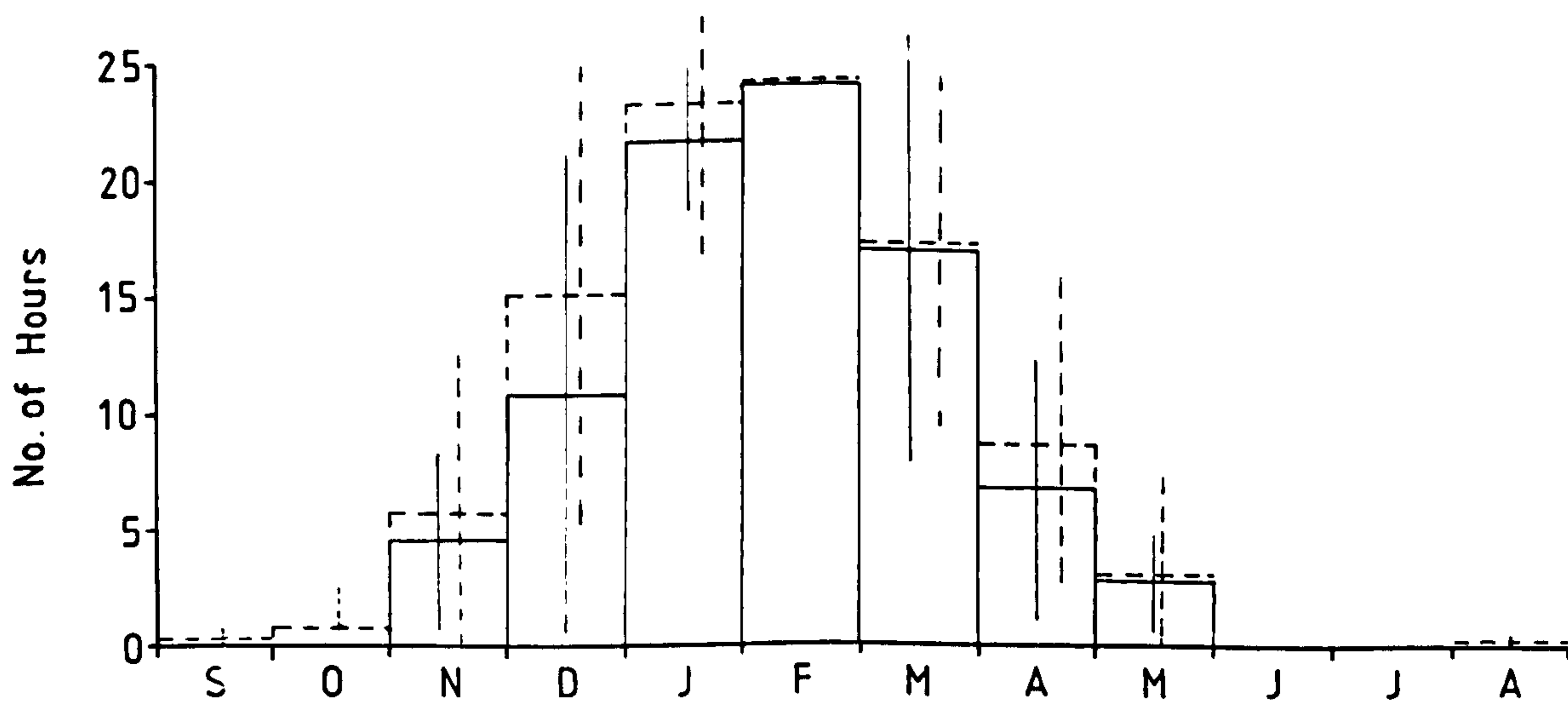
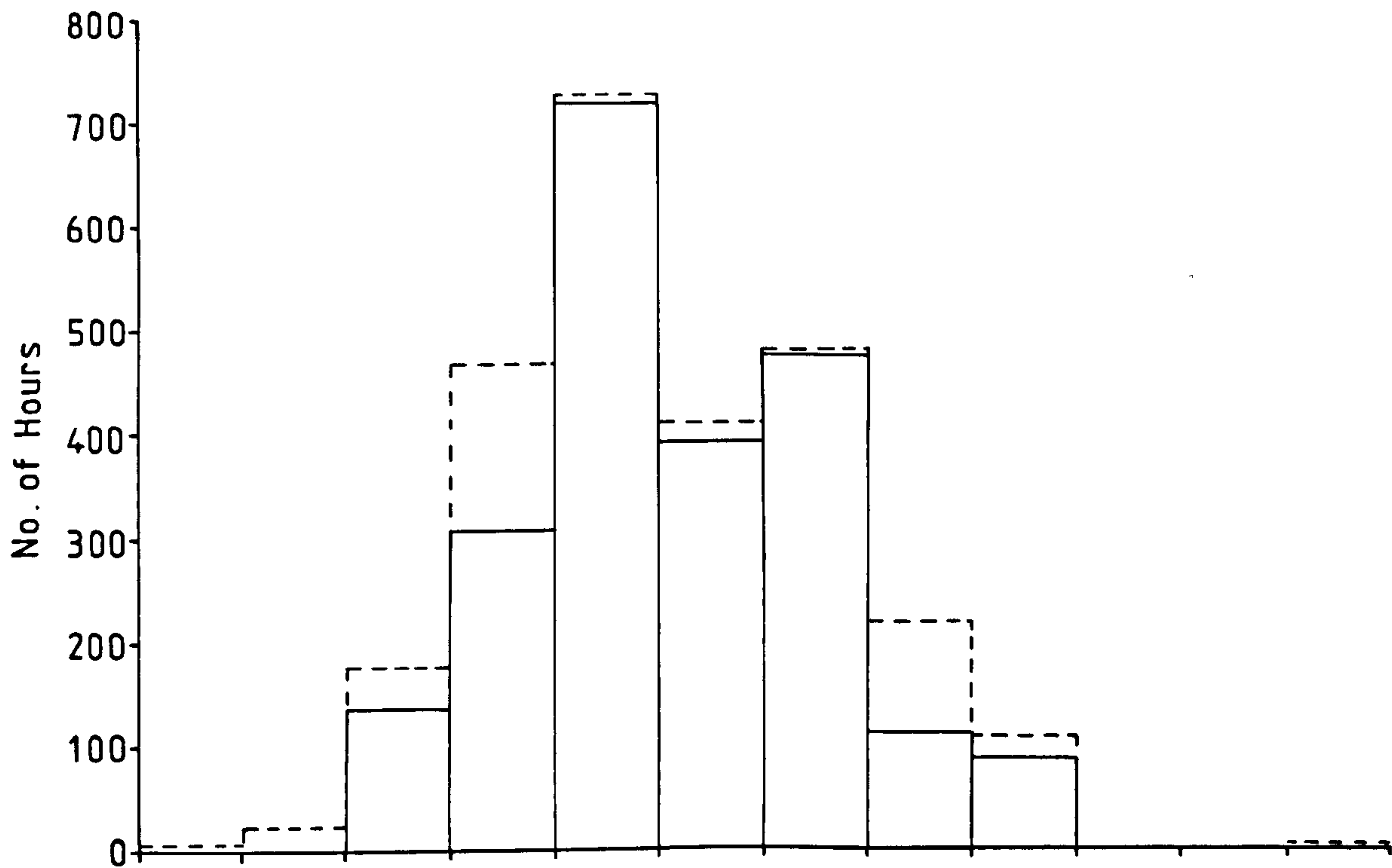


Fig. 40 (a) Number of hours of sub-zero temperatures.

Fig. 40 (b) Mean hourly duration of sub-zero temperatures (including standard deviations).

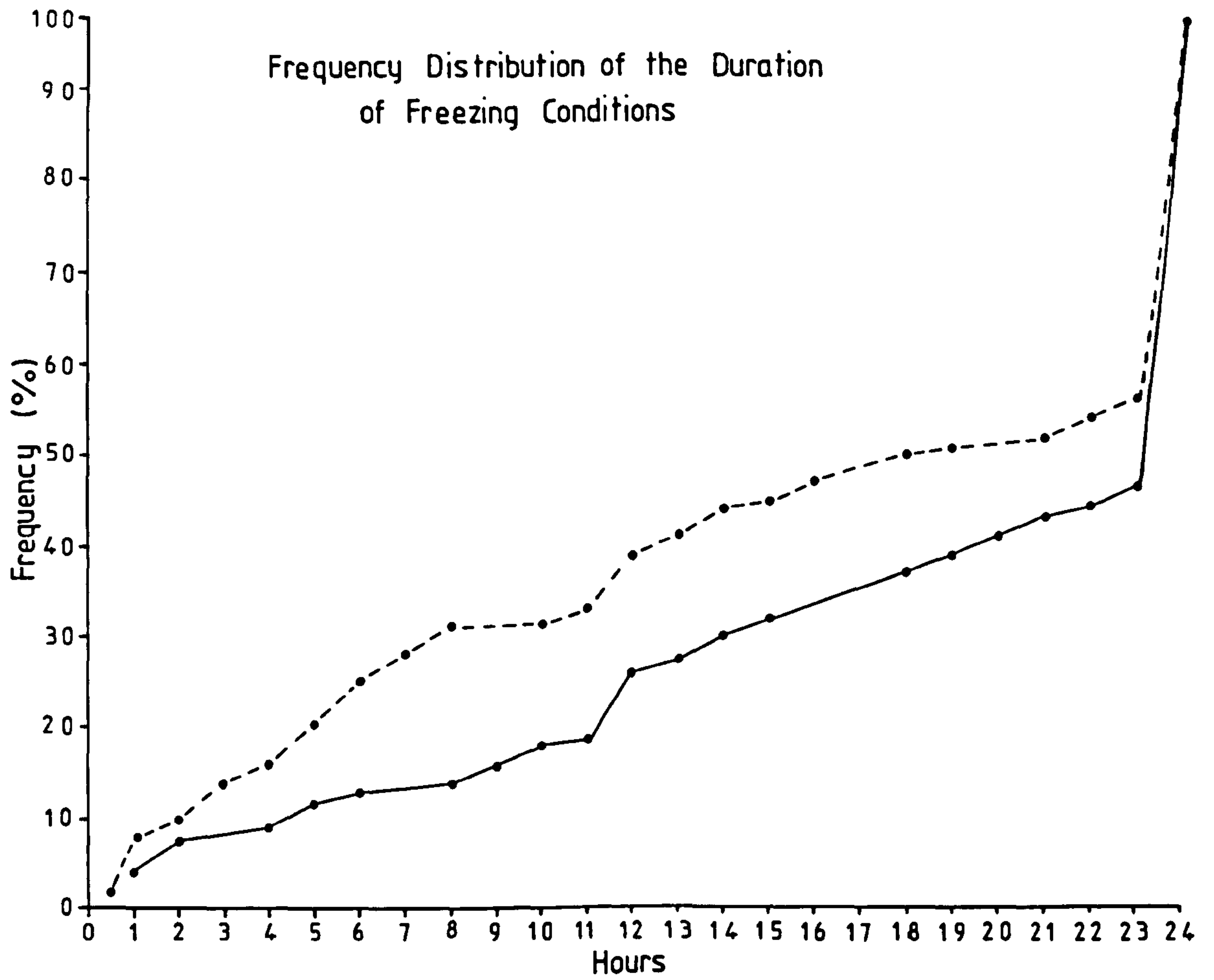


Fig. 41 Cumulative frequency distribution of the duration of freezing temperatures.

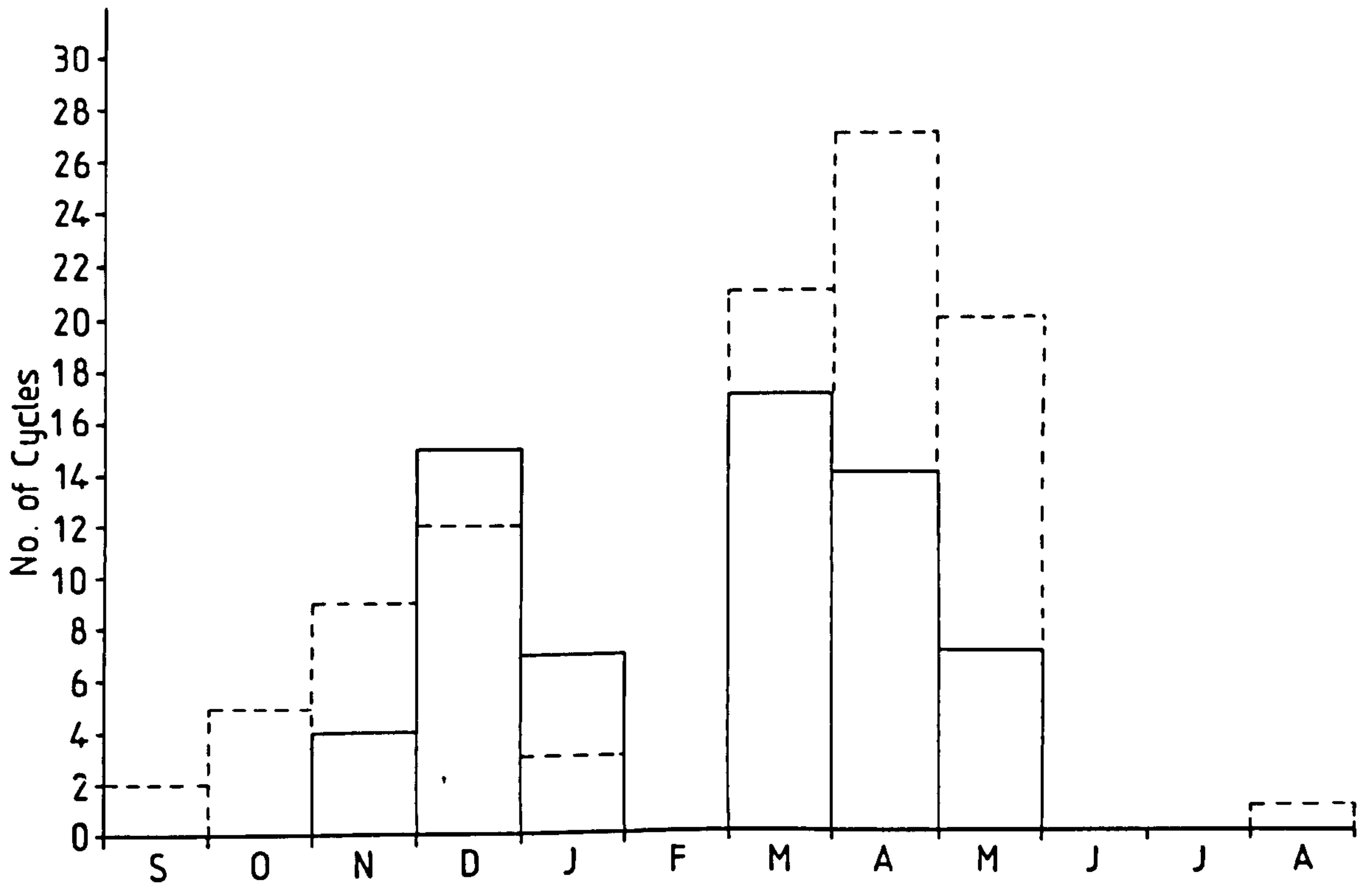


Fig. 42 Number of freeze-thaw cycles.

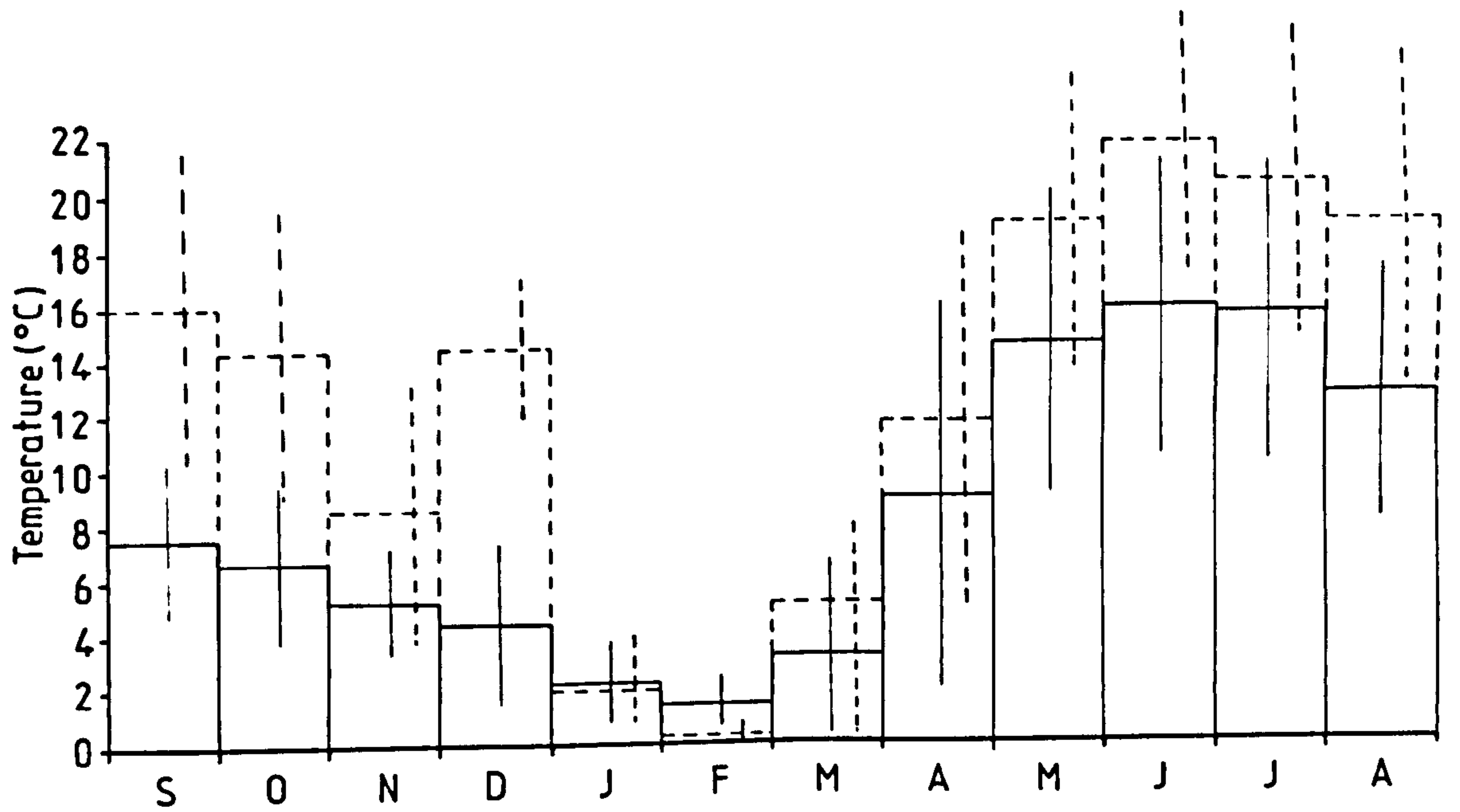


Fig. 43 Mean monthly temperature variability. (including standard deviations).

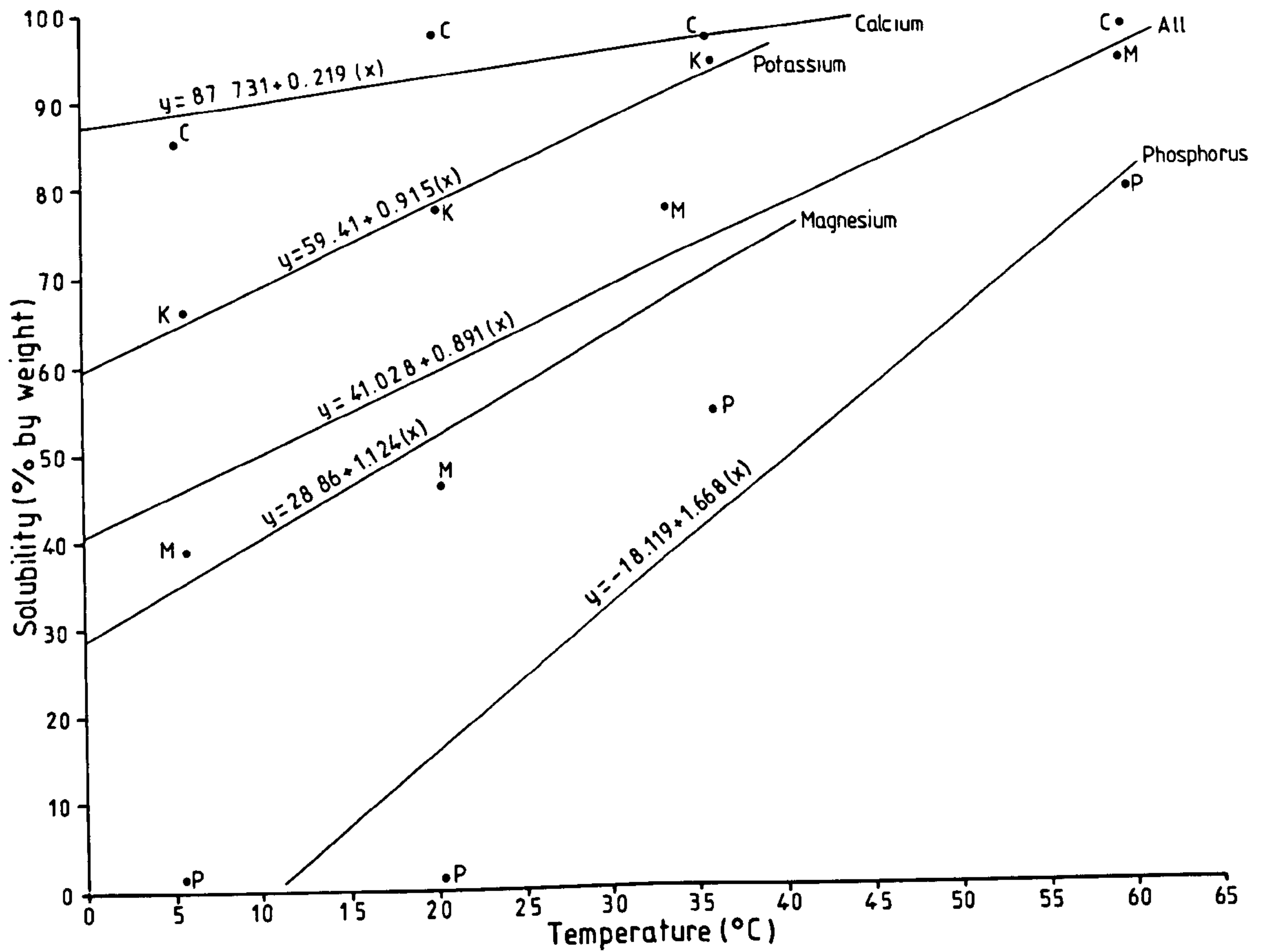


Fig. 44 Solubility of calcium, magnesium, potassium and phosphorus salts at different temperatures.

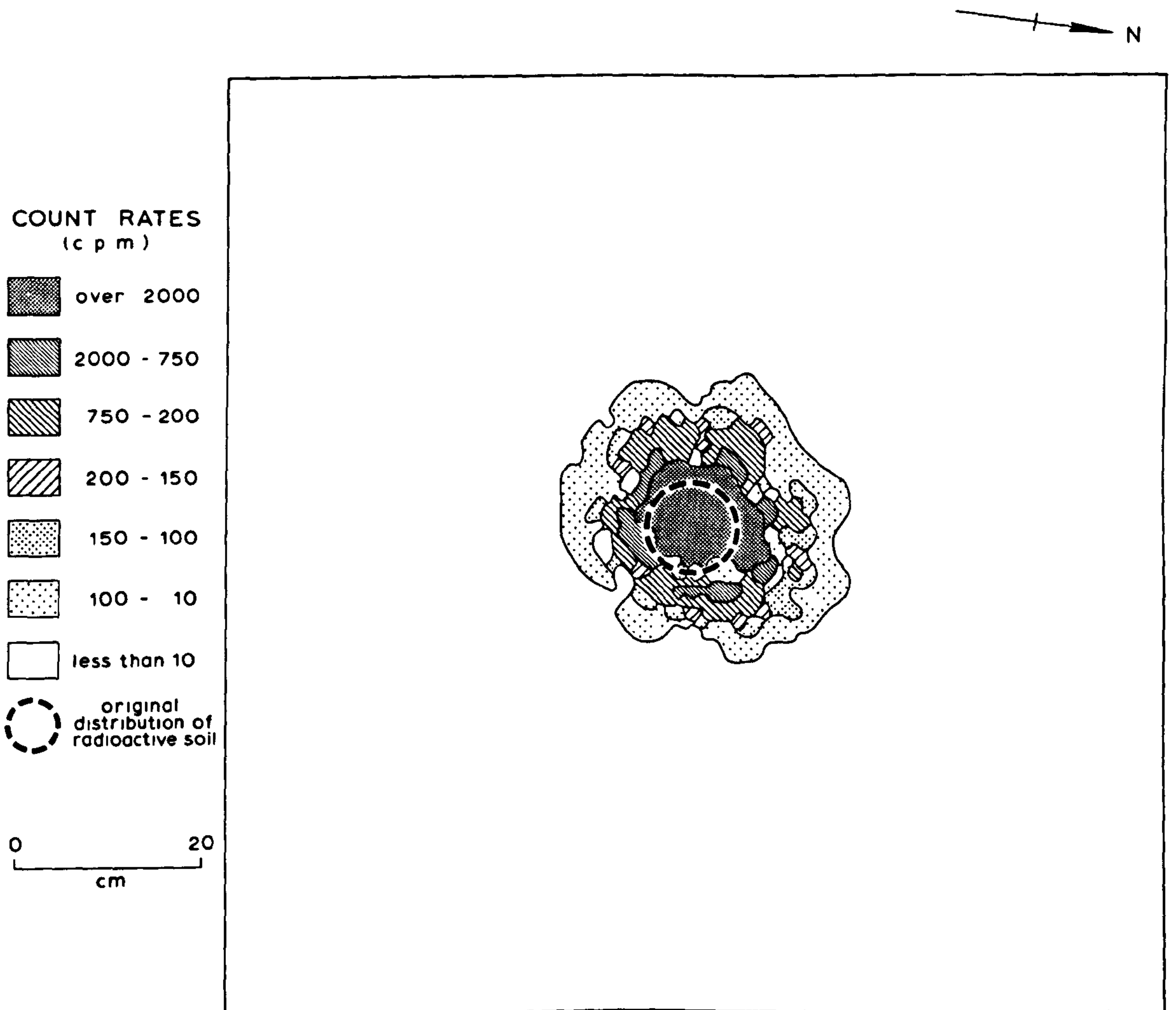


Fig. 45 Map of soil movement over vegetated quadrat (6 month exposure).

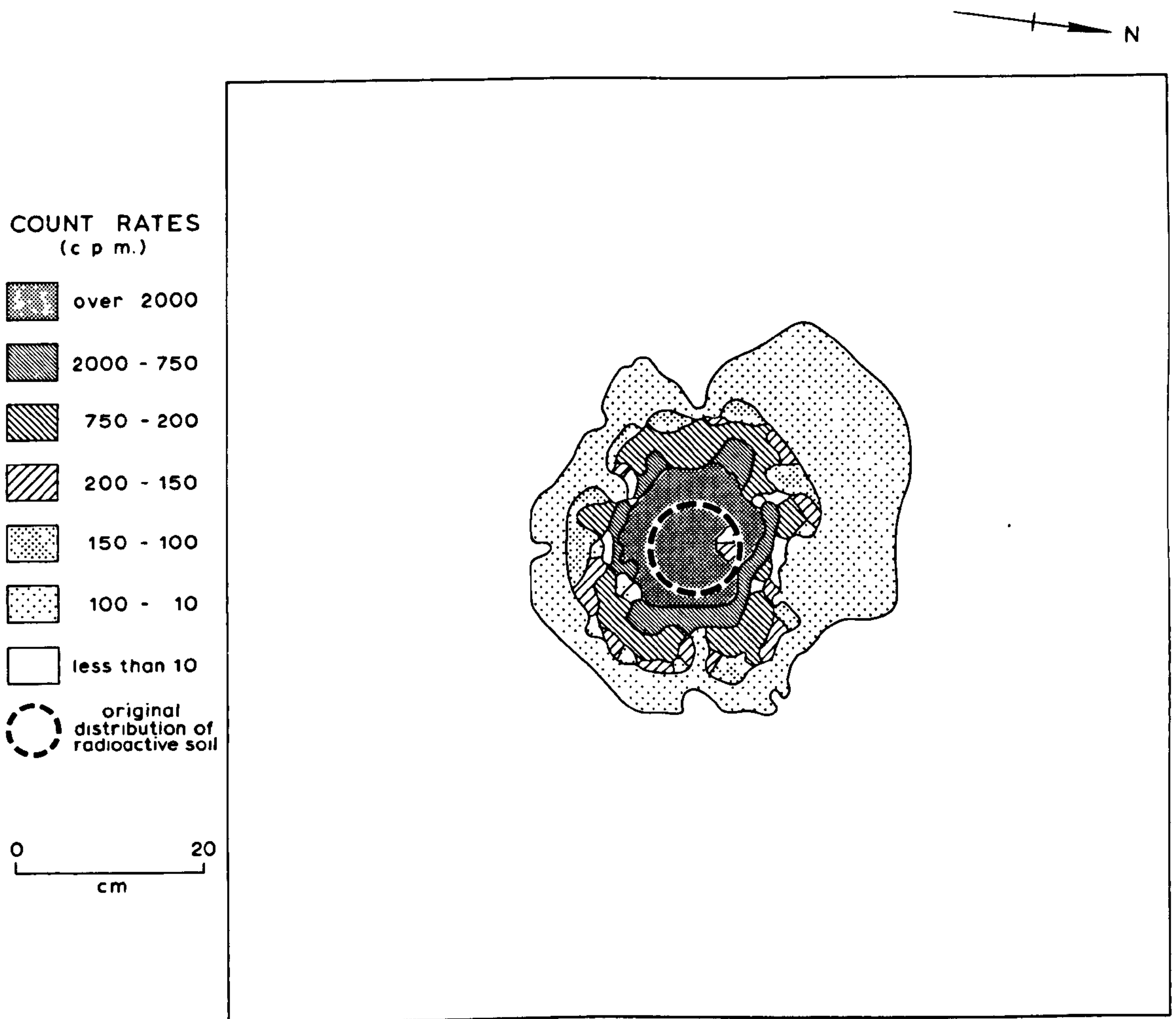


Fig. 46 Map of soil movement over burnt quadrat (6 month exposure).

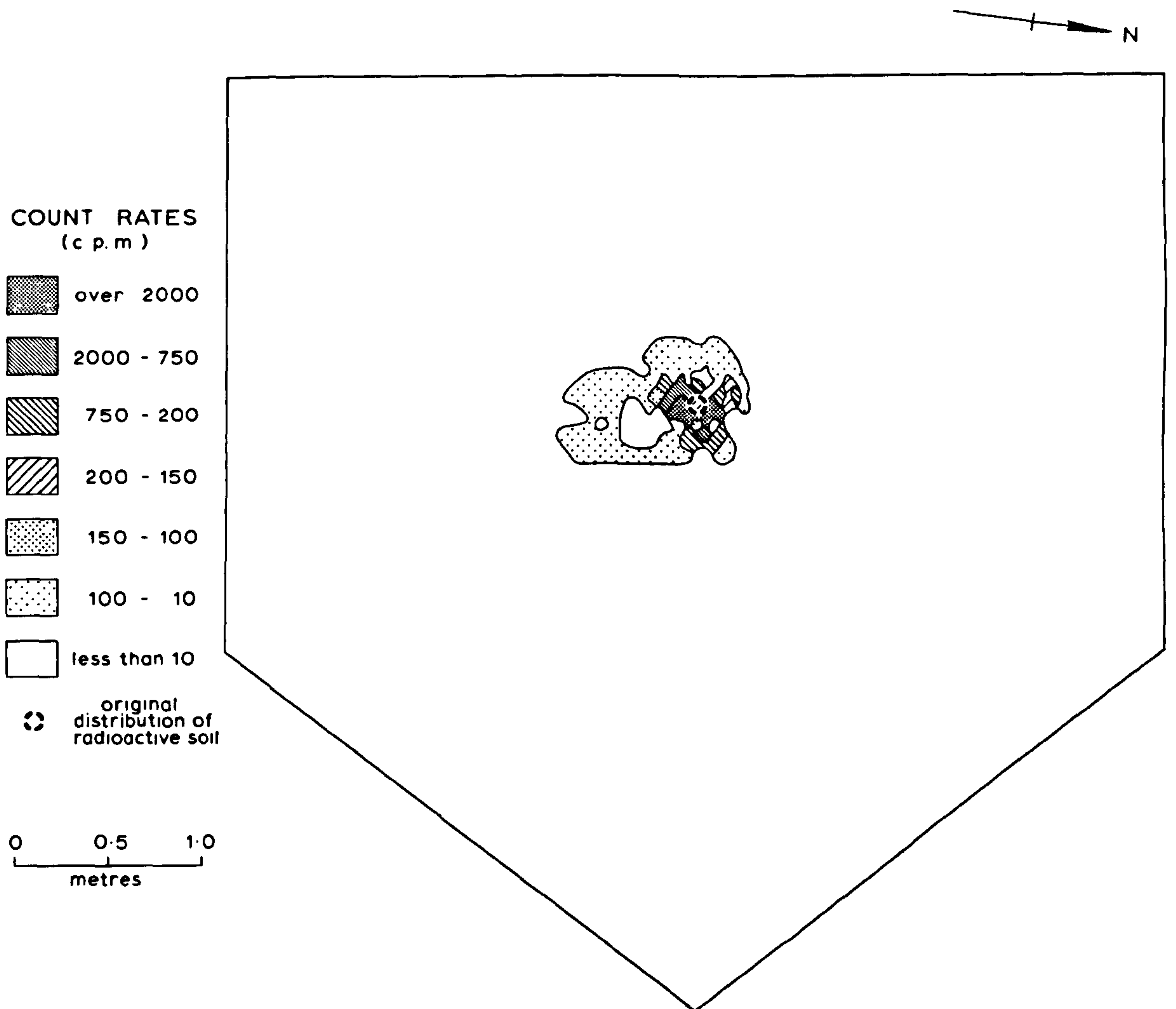


Fig. 47 Map of soil movement over vegetated runoff plot (11 month exposure).

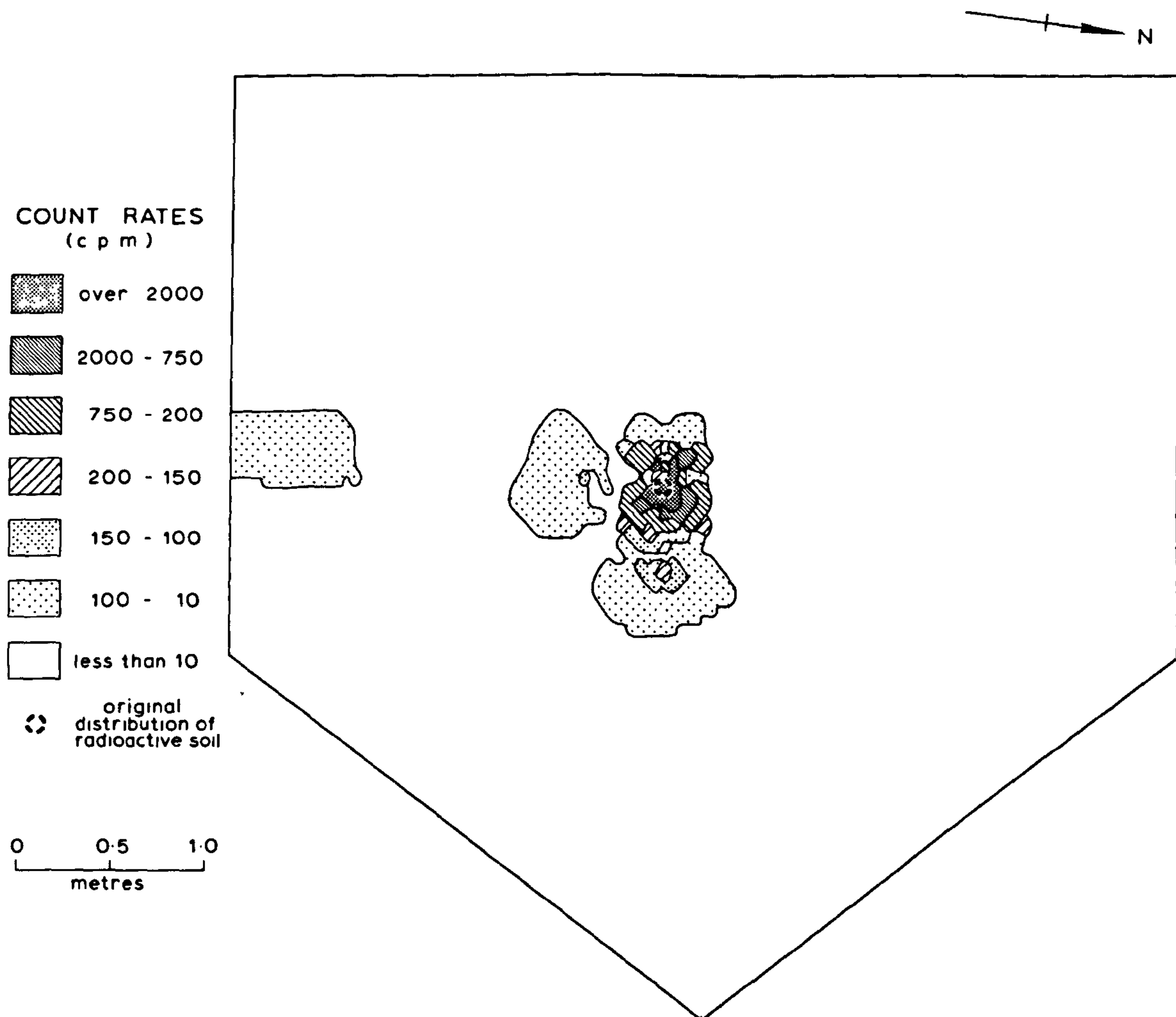


Fig. 48 Map of soil movement over burnt runoff plot (11 month exposure).

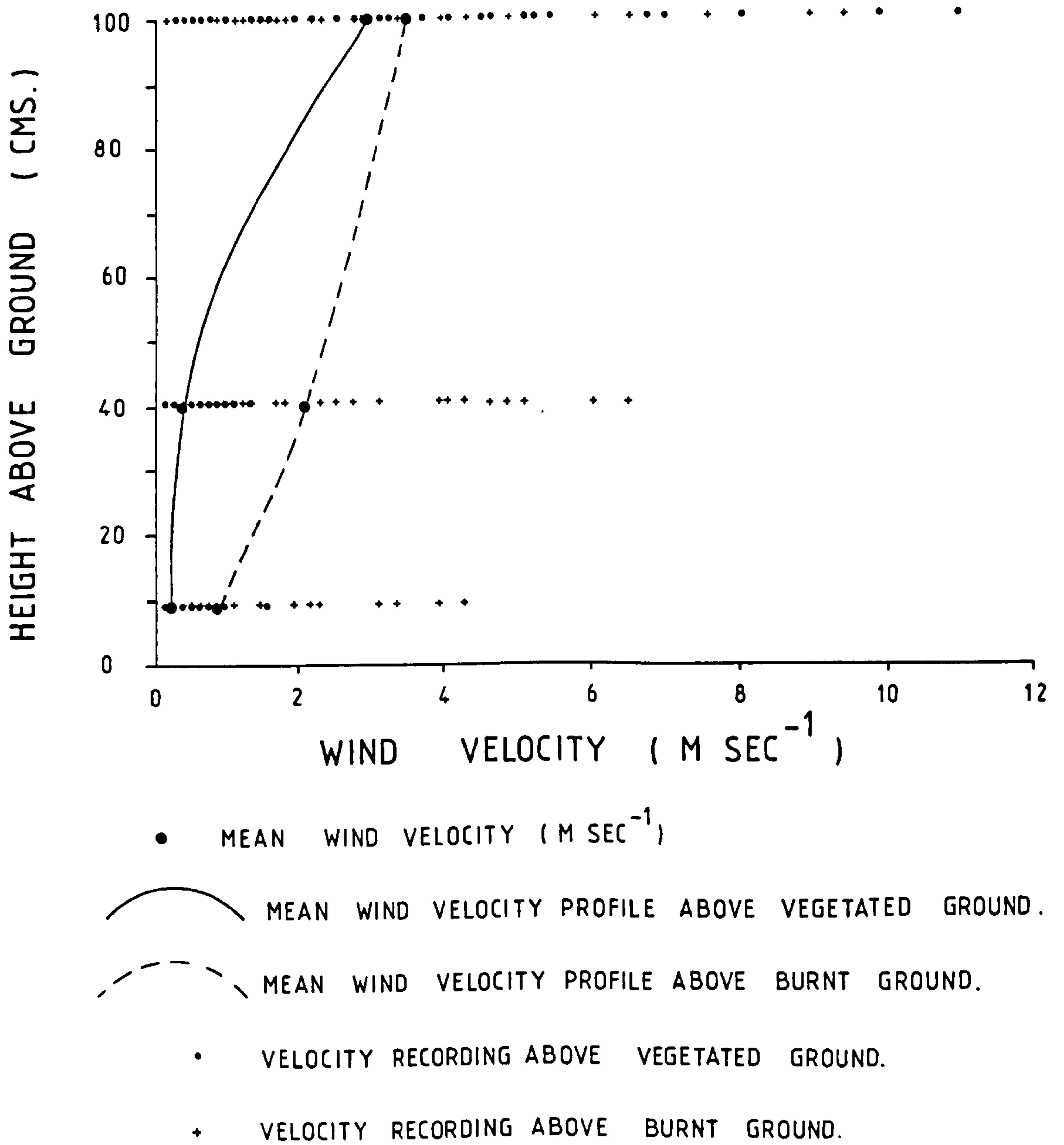


Fig. 49 Wind velocity measurements above burnt and vegetated ground :
Egton High Moor.

OVERLEAF.

Fig. 50 Precipitation, runoff and sediment loss recorded on the
 Sneaton High Moor runoff plots.

