THE EFFECT OF DIRECT DRILLING AND SOIL TYPE ON SOIL ATMOSPHERE COMPOSITION

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I declare that the thesis presented here has been composed by myself and that the work involved is my own.

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CONTENTS

ABSTRACT

A study of the soil atmosphere in soils ploughed and cultivated normally and under long-term direct drilling was made in two soil types throughout a two year period, 1973 to 1975. Probes were sited at two depths, 15 cm and 30 cm, in the two cultivation treatments, mouldboard ploughing to a depth of 20 cm and no-tillage, and in plots with different soil types, a sandy loam (Macmerry series) and a sandy clay loam (Winton series). Spring barley (cv Zephyr) was grown every year.

Soil atmosphere samples were withdrawn at weekly intervals and analysed by gas chromatography for carbon dioxide, oxygen, methane and ethylene.

The sites were sampled for moisture content, bulk density and temperature to aid the interpretation of the results.

In the first growing season the soil atmosphere had a higher carbon dioxide and lower oxygen percentage than in the second, this being related to a higher rainfall and temperature in the first season. Soil atmosphere composition was similar in the two winters. The methane component of the soil atmosphere declined throughout each growing season as soil moisture declined but levels were found to be higher in 1974 than 1973.

Ethylene was not detected regularly and not in any appreciable quantity. There was a greater incidence of detection from probes sited in no-tillage plots at a depth of 30 cm. Oxygen levels, as sampled, have little influence on ethylene in the soil atmosphere.

In a comparison between the treatments, no-tillage and ploughing, the carbon dioxide percentage of the soil atmosphere was always higher and the oxygen percentage lower, in the first growing season only, under no-tillage. This was related to a markedly lower air filled porosity in this treatment. Similarly in the first growing season differences in the

soil atmosphere between soil types were seen with a higher carbon dioxide and lower oxygen percentage in the Winton soil. This soil was consistently lower in air filled porosity but only at the low levels found in the first, wetter, growing season was this difference reflected in the composition of the soil atmosphere. The soil atmosphere at 30 cm was higher in carbon dioxide and lower in oxygen than the soil atmosphere at 15 cm.

The soil was also sampled at monthly intervals for one year and incubated anaerobically in the laboratory. This showed that throughout the year the soil did have the capacity to produce ethylene.

PTFE tubing as a soil atmosphere sampling tool was investigated and shown to be successful.

CHAPTER ONE

LITERARY REVIEW

The soil atmosphere is the air in the soil, it occupies those spaces between soil particles which are not occupied by water. It is this free pore space, the proportion of the pore space that is not occupied by water, which is important in the aeration of the soil. It has been suggested that 10% of the volume of the soil, in well drained soil, should be free pore space for adequate aeration. O'Connell has collected data to show that this 10% figure quoted may be the limiting condition for adequate root growth in most British agricultural soils where other stresses are absent. (O'Connell, 1975). Further, it has been suggested that this pore space should form a continuum throughout the depth of the soil. (Baver and Farnsworth, 1941), (Stephenson and Schuster, 1937).

The need for a continuum of pores throughout the soil to give adequate aeration should be stressed. Poor aeration can occur in a soil when the free pore space is restricted and connecting pores are blocked. Microhabitats exist in such situations. It can be assumed that the composition of the soil atmosphere is unique in these microhabitats, so that anaerobic conditions may exist in some of these microhabitats whilst in surrounding areas the oxygen concentration is high.

Further, the size of the pores within the soil structure is important. The mechanisms of gaseous exchange are dependant upon the size and shape of the pore structure. Air permeability is proportional to the total cross sectional area of the pore space free for air flow, to the square of the radii of the constituent pores, and inversely to the length of the path travelled. The coefficient of diffusion of a gas is defined as the amount of gas passing through unit cross section area, under unit concentration

gradient, in unit time. In the absence of obstruction this is given as Do. In the soil, where there is obstruction, the coefficient of diffusion of a gas will be reduced to a value D. D is related to Do in an equation where the length of pores in the soil, and the volume of pore space is considered so showing the influence of pore structure on gaseous diffusion. (Currie, 1970).

The composition of the soil atmosphere differs from that of the air by virtue of microbial activity and plant root respiration. The gas evolved from a soil can contain any of the gases produced during microbial decomposition or dissimilation of soil substrate and also any gas produced by the plant environment.

Russell and Appleyard, (Russell and Appleyard, 1915) gave the following percentages by volume as the mean composition of the soil air:

	Soil air	Atmosphere
Nitrogen	79.2	79.01
Oxygen	20.6	20.96
Carbon dioxide	0.25	0.03

The oxygen content of the soil air was lower than in the atmosphere and the carbon dioxide composition was given as eight to nine times higher. These figures are the mean composition of the soil air but within the soil there are limitless variations.

An indication of the microbial activity of the soil is provided by the gases that are evolved, and found in the soil atmosphere. Carbon dioxide and hydrogen are evolved during the anaerobic dissimilation of carbohydrate, methane from further metabolism of non-gaseous products of primary fermentation (Barker, 1956) and nitrogen, nitrous oxide and nitric oxide by the activity of denitrifying bacteria (Cady and Bartholomew, 1960). Ethylene has been detected in anaerobic conditions. It has been suggested that Mucor hiemalis, which is known to be widespread in soils, and

unidentified soil yeasts may be important sources of ethylene in the soil. Glucose and methionine were required as substrates in soil culture for the continued production of ethylene (Lynch, 1972). These substrates would probably be available in soil from the breakdown of more complex carbohydrates and peptides. One apparent paradox, however, is that oxygen promoted ethylene formation in pure culture investigations with M. hiemalis. It has been suggested that, in the field, a period of anaerobiosis may be necessary to mobilize the substrates for ethylene formation (Lynch, 1975). Certain experiments suggest that a small group of aerobic micro-organisms decompose ethylene in the soil (Cornforth, 1975).

The composition of the soil air at any one point is determined by the difference between the rate of production and utilization of gases by plant roots and soil micro-organisms and the rate of their movement away from this zone either into the deeper subsoil or into the atmosphere.

Various factors affect the movement of gases through the soil. These include soil texture, other physical conditions, and the moisture content of the soil.

Variations from the mean.

There is limitless variation in the composition of soil atmosphere on a small scale view because of the very heterogeneous nature of the soil environment. There are also broad general trends of variation such as with depth, organic matter content of the soil, and soil texture.

Any soil characteristic that is responsible for a large air capacity, such as a coarse soil texture maintained free of water, favours a lower carbon dioxide content and a higher oxygen content of the soil air, because there is less obstruction for gaseous diffusion.

Because the surface layer of the soil is in gaseous exchange with the atmosphere the soil air in this region is found to be only slightly different to that of the air. The concentration of carbon dioxide increases and that

of oxygen decreases with depth (Smith, 1974), because of the longer pathway for these gases to exchange with the atmosphere. This general trend of higher carbon dioxide and lower oxygen with depth has been found to be generally true in all seasons of the year. (Boynton and Reutter, 1938). However, because diffusion in the gas phase is so rapid, gradients of oxygen partial pressure against distance are usually too small to be measured. Thus, the composition of any gas filled channel that extends to the soil surface will not be appreciably different from the composition of the air above the soil surface. Measurements of diffusion coefficients on wet and dry materials indicate that there are no serious obstructions to diffusion in the gas phase when the total gas filled pore space exceeds 12%, (Currie, 1962), (Wesseling and Van Wijk, 1957). Thus it is indicated that if the gas filled pore space of the soil is above this value the oxygen content of the soil atmosphere will almost certainly be similar to that of the air.

The presence of growing plants tend to reduce the oxygen content of the soil air and increase the carbon dioxide content. Respiration rates increase when a soil is cropped. Möller showed that in the soil air from cropped land there was ten times more carbon dioxide than in the air from fallow land (Möller, 1879). Part of the increase in respiration rates is caused by the roots themselves and part is the result of the stimulus that a supply of fresh root residues and easily digestible organic matter gives to the micro-organisms. Currie (Currie, 1975) using soil respirometer tanks made the observation that in one year the maximum respiration rate on one of the cropped tanks was three times that for the bare soil. This maximum respiration rate occurred when the crop of dwarf beans had reached full maturity in August and September. The stage of growth of the plant thus has some bearing on variations in the composition of the soil atmosphere.

The effect of cultivation is also important when considering broad trends of variation in the soil atmosphere. Any cultivation treatment

which reduces the bulk density of the soil, and therefore increases the air porosity, will have the effect of increasing the aeration status of the soil. When soil atmosphere studies were conducted from Letcombe Laboratory it was found that direct - drilled areas of a field were on average less well aerated than ploughed soil, (Smith, 1974).

The effect of organic matter is to stimulate microbial activity, and hence the production of carbon dioxide and also ethylene, (Smith et al, 1969). Russell and Appleyard showed that manuring increases the carbon dioxide content of the soil air, (Russell and Appleyard, 1915). Thus microbial decomposition is an important factor in carbon dioxide production. Peat soils usually contain more carbon dioxide than mineral soils and considering this Smith et al studied the amount of ethylene produced after ten days from six soils with organic matter contents ranging from 1.4 to 38%. They found that the amount of ethylene produced was closely related to the organic matter content of the soil up to about 10%, which is the range commonly found in agricultural soils, (Smith et al, 1969).

There are considerable seasonal fluctuations in the composition of the soil atmosphere primarily due to seasonal changes in moisture content and temperature. The low oxygen content of heavy subsoils in the winter is associated with moisture content. When the soil dries out in the summer months the oxygen content of the subsoil increases. The minimum oxygen level and the extent of the period of low oxygen seem to be determined by accumulated precipitation, by soil texture and compaction, and by depth, (Boynton and Compton, 1944). Smith ~~and Dowdell~~ et al (1974) substantiated this seasonal fluctuation of oxygen content, associated with the moisture content of the soil, in a heavy clay soil. They also found a clear relationship between high moisture content and the production of ethylene in a sandy loam. Soil temperature was also found to influence the production of ethylene. Concentrations of ethylene were found to rise logarithmically with soil

temperature during the spring. The carbon dioxide content of the soil atmosphere also has a seasonal fluctuation associated with temperature. Maximum levels of carbon dioxide are reached during the summer months when soil temperature is relatively high, even though oxygen percentage may be relatively high at the same time, (Boynton and Compton, 1944).

Seasonal variations are imposed upon any general trends, for example the oxygen content of the soil decreases with depth throughout all seasons of the year, (Boynton and Reutter, 1938).

Gaseous exchange

The movement of gases through the soil and the exchange of the soil gases with the atmosphere is by diffusion and also by the influence of metereological factors which cause mass flow of the soil air.

Soil temperature changes, barometric variations, wind action, and rainfall may cause mass flow of soil gases.

Considering soil temperature: warm air moving upward and expansion and contraction of air in the pores of the soil, under the influence of temperature changes, could conceivably cause some exchange among the various soil horizons and with the atmosphere. However, temperature changes, whether diurnal or seasonal, are greatest at the soil surface and decrease exponentially with depth so that gas exchange by this mechanism must be confined to the upper layers of the soil. Keen, (Keen, 1931) pointed out that because there is a phase lag in temperature at depth there are periods during summer days when the surface soil is colder than the soil at depth. He calculated the amount of convective flow, and hence exchange, that might occur in those circumstances and concluded that it is unlikely that temperature changes play anything more than a minor role in soil aeration.

Barometric pressure variation could be involved in gaseous exchange if these changes were reflected within the soil pores and thus resulting in gaseous volume changes in accordance with Boyle's law. With a change in atmospheric pressure above the soil surface, air will flow into the soil

as the pressure rises, and out as it falls, until an equilibrium is restored between the soil and the atmosphere. For practical purposes the attainment of equilibrium can be regarded as instantaneous. In an experiment when a barograph was buried to a depth of ten feet in a soil a lag period for changes in atmospheric pressure could not be detected, (Bouyoucos and McCool, 1924).

Wind action can be seen to be influential in facilitating gaseous exchange between the surface layer of soil air and the atmosphere in bare, porous, unprotected soil but would have little effect where there is a vegetation cover or a compact surface layer. The effect of the wind would be to cause mass flow in the soil. A pressure difference could also be set up between the windward and leeward sides of a cultivation ridge, a clod or other surface roughness, and this may cause air to flow within the soil.

Rainfall is the most influential of the metereological factors in bringing about gaseous exchange in the soil layers. The penetrating water carries dissolved gases and also displaces air in the pores of the soil, (Richards, 1917). The wetting front advances downwards subject to more water being applied above, (Childs, 1969). Therefore mass flow of the soil atmosphere and introduction of dissolved gases from the air occurs with the perculation of the water through the soil. Also, rainfall reduces the air filled fraction of the pore system. Uptake of water by roots and evaporation from the soil surface increases free pore space.

Buckingham, (Buckingham, 1904), was one of the first to apply the kinetic theory of diffusion of gases to the movement of gas through the pore space of the soil. He showed a definite correlation between the free pore space and the diffusion constant, the rate of flow of gas through the soil pore space as a result of kinetic movement. By his calculations the only soil factor controlling the rate of diffusion is the free pore space.

Other factors such as soil texture, and moisture, for example, do not affect diffusion directly but only as they alter the free pore space.

Do is the coefficient of diffusion of a gas in the absence of obstruction. Where solids and liquids impede the progress of the molecule Do is decreased to a value D. The ratio between the coefficient of diffusion of a gas with or without obstruction is termed the diffusion ratio D/Do. The factors which determine this ratio are complex but the diffusion ratio is determined in part by porosity, ϵ (Currie, 1970).

It has been established considering simple particulate packings that

$$\frac{D}{Do} = \epsilon^m$$

where m is a factor for particle shape, numerically equal to 1.5 for spheres and increasingly larger for more complicated shapes. Particles which are themselves porous, for example soil crumbs, apparently also fit this relationship and it has been possible to estimate diffusion coefficients, Dc, for diffusion within the crumb structure, (Currie, 1965).

It had been assumed in earlier work that solids and liquids would have a similar effect on the diffusion ratio by altering porosity in the same way. This, however, is not the case. A particulate solid phase assumes more or less a random distribution within a given space, water is, however, confined by surface tension to assume certain positions within the pores of a matrix, (Currie, 1970). So water not only alters the diffusion ratio in a different way to solids by affecting the porosity differently but it offers less of an obstruction to diffusion than solid imporous particles. Diffusion does, of course, occur through the aqueous phase of soils but it is 10,000 times slower than in the gas phase.

Therefore, if diffusion is to bring about adequate ventilation of the soil it is important that the soil pores should be continuous with each other and with the atmosphere. The importance of compaction pans in the soil profile and surface crusting is to be emphasised. These impede diffusion and gaseous exchange because the free pore space is restricted.

The effect on plant root growth.

The principal gases in the soil atmosphere whose effect on plant root growth have been studied are oxygen, carbon dioxide and ethylene. Oxygen and carbon dioxide are directly involved in root respiration and therefore the effects when their concentrations vary has been considered important.

The effect of ethylene on plant roots has only recently been studied. This gas was detected in the atmosphere of anaerobic soil by K.A. Smith (Smith and Russell, 1969) and this is thought to have been the first detection of this gas in the soil atmosphere. This was probably due to the difficulty in detecting ethylene in low concentrations without modern gas chromatographic techniques. Ethylene is also present in aerobic soils. It is a plant growth hormone with the unique property that the levels in the plant are controlled by diffusion of ethylene out of the plant, (Burg, 1962), (Pratt and Goeschl, 1969).

Oxygen

The effects of variation in the concentration of oxygen around plant roots has been studied with particular emphasis on trying to find the cause of injury to plants in waterlogged situations. It is in waterlogged soils that there is an effective impediment to diffusion of soil air by water occupying the pore spaces of the soil. In these situations root respiration, together with aerobic microbial activity will reduce oxygen levels.

Lack of oxygen leads to inhibition of nutrient uptake by roots and interference with water uptake. Kramer observed the effect on plants of flooding the soil and he made the point that the injury sustained and the speed in which stress is observed in the plant cannot be explained solely by lack of water and nutrient uptake. He suggested that anaerobic conditions lead to a build up of toxic substances and also that these conditions interfere with the translocation of auxins and carbohydrates through the plant, (Kramer, 1951).

Injury due to lack of oxygen is more marked at low than at high levels of nutrition. Woodford and Gregory showed that barley seedlings could be grown for twelve days in a nitrogen atmosphere and in the absence of oxygen without being much affected as long as the nutrient concentration was four times that of an aerated solution. It was also shown that plants are more readily injured in unaerated water than in an unaerated nutrient solution, (Woodford and Gregory, 1948).

These results illustrate the difficulty in relating interpretations of experiments performed with plants in nutrient rich culture solutions to the performance of the plant in the soil because of the difference in the nutrient status of the two media.

Direct measurements of oxygen concentrations at points around plant roots in soils gave results which have led to the conclusion that unless the oxygen concentration is almost zero, at least somewhere near the rooting zone, plant growth will be unimpeded by lack of oxygen. The activities of cytochrome oxidases, the terminal oxygen acceptors in roots, are unaffected by lowering oxygen concentration until the extremely low value of 0.01 ml/ml is reached, (Greenwood, 1968).

Further, in general, aerobic microbial processes are not inhibited and anaerobic processes not induced unless the concentrations of oxygen in the soil air fall to the very low value of 2×10^{-3} ml/ml, (Greenwood, 1961). It has been estimated that water saturated aggregates would have to be greater than 2cm in diameter for there to be any oxygen free zones, (Greenwood, 1971).

It has been established that oxygen transport takes place from the aerial parts of plants to their roots and that this oxygen can supply much of the root requirements of seedlings, (Greenwood, 1968).

It has been stated that inadequate diffusion in the gas phase is unlikely to have any influence on the occurance of oxygen free zones when

the gas filled pore space is more than 12%. Therefore poor soil aeration is unlikely to restrict plant root growth in the U.K. when the gas filled pore space is more than 12%, and the soil aggregates are less than 2cm in diameter. It is only during periods of water logging, when these conditions are not met, that soil aeration may be insufficient for optimum growth.

The effects of soil oxygen are therefore such that only anaerobic regions will have any adverse effect on plant root growth. The mean composition of aerobic regions are only of academic interest as they will have no adverse effect on growth.

However anaerobic regions even if present for only short durations have a profound effect on root growth. Letey, Stolzy, and Blank studied the effect of duration and timing of low soil oxygen. They found that there is a time lag of recovery of root growth after being stunted by a low oxygen supply. Also it was shown that the low soil oxygen, as obtained by flushing the soil with nitrogen, was most detrimental during the early stages of growth following germination. Thus the number of days which a soil can be water logged without serious crop damage depends on the stage of plant and root development, (Letey et al, 1962).

Huck also studied this problem. He measured the elongation rates of cotton and soyabean taproot while the oxygen content of a gas stream that passed through the soil was varied. Elongation ceased completely 2-3 minutes after all the oxygen had been purged from the system by a stream of nitrogen gas. It returned to normal shortly after 20% oxygen was returned to the system as long as the period of anaerobiosis was not greater than 30 minutes. With the period of anaerobiosis exceeding 30 minutes, increasing proportions of tap root death resulted until all those of cotton were killed at three hours and all soyabean taproots at five hours. Tissue death did not extend to older tissue, but was confined to the region of elongation, (Huck, 1970).

In the same experiment, after a period of anaerobiosis, lateral root

initiation and development was observed immediately above the killed portion. Similarly in flooded soil different root formations have been observed as new adventitious roots grow. This led Kramer to make the suggestion that roots which are produced in water are different anatomically or physiologically, or both, from roots produced in well aerated soil. It has been observed that roots produced in poorly aerated media usually contain much larger intercellular spaces than those produced in well aerated media. It has been suggested that these air spaces are produced by collapse of cells following death due to lack of oxygen. (Kramer, 1951)

Thus the form and distribution of roots through a volume of soil could be significantly influenced by a period of anaerobiosis of even a few hours.

Carbon dioxide

The effect of carbon dioxide may be either a direct toxic effect on microbial or root activities or may be indirect by its effect on the pH of the soil. For each tenfold increase in carbon dioxide concentration in aqueous solution there is a fall of about half a pH unit. Therefore, depending on the buffering capacity of the soil, with a high carbon dioxide concentration unsatisfactorily low pH levels may be reached.

Exposure of root systems to a high concentration of carbon dioxide has been shown to cause an immediate reduction in water absorption (Kramer, 1940). This effect was further studied by Kramer and Jackson who looked at injury to tobacco plants while flooding and aerating the soil, or saturating it with carbon dioxide. Their results indicate that carbon dioxide has more of an immediate effect on plants than deficiency of oxygen. Tobacco plants in soil, at field capacity, but saturated with carbon dioxide were more severely wilted and showed moderate chlorosis whilst similar plants in soil at field capacity but saturated with nitrogen, showed only a moderate degree of wilting, (Kramer and Jackson, 1954).

Other studies have shown that when the partial pressure of oxygen was 0.21 atmospheres the minimum carbon dioxide partial pressure around roots that had any toxic effect was generally less than the oxygen partial pressure and as low as 0.08 atmospheres for cotton, (Tackett and Pearson, 1964). But when carbon dioxide and oxygen partial pressures were both varied, so that the effect of low oxygen and high carbon dioxide were studied together, plant functions were not appreciably reduced until the ratio of CO_2 : O_2 partial pressures was greater than one, (Harris and Van Bavel, 1957). It has been suggested that this situation will not arise unless the carbon dioxide partial pressure exceeds 0.1 atmospheres.

Field data, from samples taken in the larger pores of soil, have shown that carbon dioxide percentage fluctuations during the growing season were much less than the fluctuations of oxygen, (Boynton and Compton, 1944). Further, theoretical predictions are that in the aqueous phase of aerobic soils carbon dioxide partial pressure/distance gradients should be less than one-twentieth of the similar gradients of oxygen. Greenwood has provided evidence to confirm the theoretical predictions and concludes that the partial pressure of carbon dioxide in the aqueous phase of soils would never be more than 1% of an atmosphere greater than in the gas phase. This is in soil containing no oxygen-free zones, (Greenwood, 1970).

It therefore appears that high carbon dioxide concentrations will only be encountered when there are oxygen free zones in the soil. Both the effects of high carbon dioxide and oxygen free zones therefore ought to be found together in the field.

Ethylene

The root system of barley seedlings that have been exposed to ethylene take on a stunted appearance with the main axes and laterals swollen, curved and covered densely with root hairs (Cornforth and Stevens, 1973, Crossett and Campbell, 1975). The gas has been found to have an inhibitory

effect on the extension of root axes of barley and other cereals at concentrations greater than 0.1 ppm. (Smith and Robertson, 1971). In a waterlogged soil, ethylene has been found at concentrations much higher than this, (Smith and Russell, 1969).

Further investigations in which sampling probes were placed at various depths in the soil, showed the highest mean concentrations of ethylene occurred after heavy rain in January, in each of the three depths 30, 60 and 90 cm. With less rainfall the levels of ethylene at the three depths dropped. A clear relationship between soil water and the concentration of ethylene was indicated, (Dowdell et al, 1972).

The origin of ethylene in anaerobic soil was investigated by laboratory experimentation. The evolution of ethylene from soil after it has been sterilised by different means was monitored and the results suggested that ethylene was produced by enzymatic and not chemical activity. Further, by the effects of temperature on the evolution of ethylene, a microbiological process was indicated to be responsible. Evidence was also obtained that appreciable evolution of ethylene did not occur until the oxygen concentration in the test soil was considerably below 2%, (Smith and Restall, 1971). As has already been discussed anaerobiosis in soil may be necessary to mobilize the substrates for ethylene formation but, in pure culture, oxygen promotes ethylene formation by M. hiemalis, (Lynch, 1975).

The biosynthesis of ethylene in plant tissue is an aerobic process, (Liebermann et al, 1966), and levels in the plant are controlled by diffusion out of the plant into the soil atmosphere, in the case of the root system.

The conclusions can be drawn that ethylene may be a significant factor in causing injury to crop plants under waterlogged conditions. Injury could be sustained in situations where anaerobic pockets occur

within a mainly aerobic soil structure. There would have to be an impediment to the escape of ethylene so that inhibitory concentrations could build up in the vicinity of plant roots. Similarly it may be postulated that inhibitory concentrations could build up where there is an impediment to diffusion of the gas from roots even though conditions are not established for the production of ethylene by soil micro-organisms.

Experiments to show the effect of varying concentrations of carbon dioxide on the action of ethylene showed that at concentrations of carbon dioxide not themselves inhibitory to root extension (below 2%) the carbon dioxide had little influence on the effect caused by ethylene. Even at inhibitory concentrations of carbon dioxide the percentage reduction in root growth caused by ethylene was similar to that at non inhibitory concentrations of carbon dioxide (Smith et al, 1969).

In an experiment where barley seeds were germinated in gas mixtures containing ethylene and various amounts of oxygen it was shown that at 21.0 per cent oxygen ethylene, up to 20vpm, had no effect on germination but decreased root growth. In five per cent oxygen mixtures roots grew more slowly than in air but were not affected by ethylene (Cornforth and Stevens, 1973).

Mechanical Impedance

When considering the effect of soil atmosphere composition on root growth the influence of mechanical impedance must also be reviewed. Mechanical impedance to root growth has a substantial influence on its subsequent growth. Pfeffer (Pfeffer, 1893), was the first to show that the energy expenditure of a root in overcoming resistances is insignificant. Thus, if the soil offers a greater resistance than the maximum pressure which the root can exert then root extension ceases. Eavis has tried to separate the effects of mechanical impedance, and those of poor aeration, where the two act together. He devised an aeration deficiency index which

is defined as the percentage change in the root growth property attributable to poor aeration and is found by the following formula -

$$\text{Aeration deficiency index} = 1 - \frac{\text{Actual root elongation (at given oxygen/mechanical impedance level)}}{\text{Root elongation at the same level of mechanical impedance in normal air}} \times 100\%$$

This eliminates the component due to mechanical impedance in the adverse effect on root elongation, (Eavis, 1972).

There is little or no physical difference in the appearance of roots grown under either conditions of mechanical impedance or poor aeration. In both cases shorter, thicker roots than those grown under normal conditions are produced.

It therefore appears that when considering adverse effects on root systems in the soil some of the factors that may be involved are anaerobic conditions, high concentrations of carbon dioxide, the presence of ethylene, and mechanical impedance to root growth. The problems arise in trying to sort out which factor is primarily responsible. In adverse conditions, such as waterlogging, it is evident that all of these factors may be present. Any adverse effect on root growth can be attributed to a combination of these factors. It can, however, be concluded that a high concentration of carbon dioxide has a more immediate effect than very low levels of oxygen and that ethylene can have an effect on root growth at non inhibitory concentrations of carbon dioxide. Mechanical impedance could also affect root growth independantly of all other restrictions.

CHAPTER 2

OUTLINE OF RESEARCH PROGRAMME

I Soil Atmosphere Studies

A long term experiment on the effect of tillage methods in a barley monocropping system was started in 1968 (Holmes and Lockhart, 1970). This experiment is a joint project run by the Edinburgh School of Agriculture and the Scottish Institute of Agricultural Engineering. It is supported by an ARC grant. The tillage methods used in the experiment are mouldboard ploughing at two depths, chisel ploughing, and direct drilling. Spring barley (cv Zephyr) is the crop used in the investigations.

It had been found that dry bulk density was higher in the top 15cm of the direct drilled plots (Soane et al, 1970). Root length in the different soil horizons was closely related to the soil bulk density. Further, the yield from direct drilled plots was constantly lower for the same nitrogen treatment, compared with ploughing. (Holmes and Lockhart, 1970). Many cases of water logging had been observed on these plots.

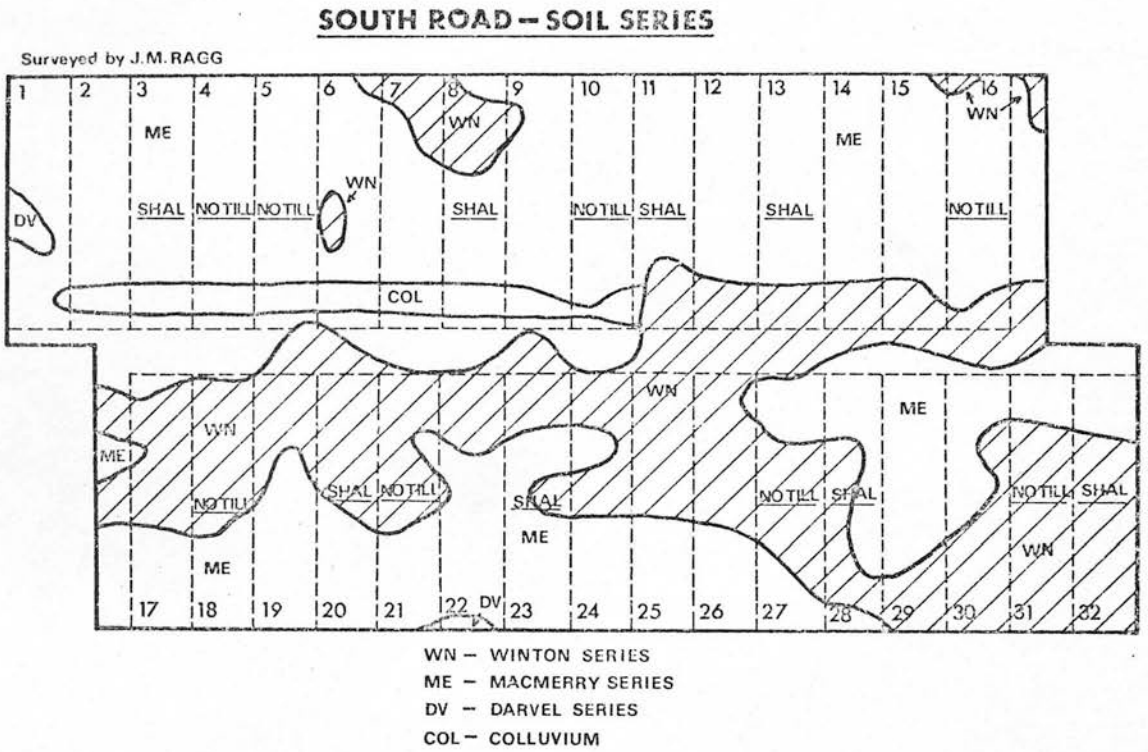
Ample evidence has been accumulated to show that the soil atmosphere has an effect on plants and also that the soil atmosphere itself is influenced by the bulk density of the soil. Thus it was felt that soil atmosphere studies in the field were required to investigate fully the effects of tillage methods in relation to continuous barley growing.

The two cultivation treatments selected for soil atmosphere studies were ploughing to a depth of 20cm and direct drilling, (or no-tillage). Mouldboard ploughing to a depth of around 20cm is the common practice for spring cereals. Under direct drilling, seed is drilled into the uncultivated stubble. A triple disc drill was used. Weed control in this no-tillage method of cultivation is by chemical means. Paraquat was used until 1974

and then the chemical Glyphosphate was employed instead. Direct drilling with its saving on fuel, machinery and labour costs, together with overcoming certain problems associated with ploughing is beginning to find a place in agricultural practise.

The soil within the experiment consists broadly of two soil series.

Figure 1



The two blocks of the experiment are each, to a large extent, of the different soil types. Replicates 1 - 4 are largely Macmerry soil series and replicates 5 - 8 are with a majority of Winton soil series (Figure 1).

The Winton soil has a higher proportion of clay than Macmerry in the upper horizon. It is a fine textured sandy clay loam overlying a clay subsoil. The Macmerry soil is a friable medium textured loam overlying a sandy - clay loam subsoil. Macmerry is therefore a lighter soil.

Because of this situation in the field it was possible to include a study of the soil atmosphere within two differing soil types.

It has been shown that the composition of soil atmosphere is related

to factors such as soil moisture, and temperature, also that there is a correlation between free pore space and the diffusion constant. Data on these factors was therefore recorded to aid in the interpretation of the results. This data includes soil moisture content, °/oW/W, rainfall figures and soil temperature recordings. Bulk density measurements were also available from which air filled pore space could be calculated, (with acknowledgement to SIAE).

II Flask analysis

As an integral part of soil atmosphere studies in the field situation a laboratory experiment was designed to study the capacity of the soil to produce ethylene. It was hoped that it would be possible to predict from this whether ethylene could be a contributory factor to poor yields. If the soil was found not to have the capacity to produce ethylene, given favourable conditions in the laboratory, then, even if conditions were suitable in the field, it may be that ethylene production could be discounted as a contributory factor to poor crop yields in these soils.

Soil samples were taken from the particular field being investigated at various stages in the year. The rationale behind seasonal sampling to monitor the capacity of the soil to produce ethylene was the evidence that ethylene production in the soil varies with the state of decomposition of the organic matter in the soil and with the availability of necessary substrates (Smith et al, 1969), (Lynch, 1972).

Because, in the field, a period of anaerobiosis may be necessary to mobilize the substrates for ethylene formation (Lynch, 1975) these soil samples were incubated under anaerobic conditions.

III Clod Work

As an addition to the above studies an attempt was made to investigate soil atmosphere within clod structures in a laboratory experiment. If clods are present in the soil roots could be exposed to a different

environment within these clods. It is therefore important to have some data on the gas composition of this microenvironment. A sampling tool had to be developed for this.

The use of PTFE tubing as a sampling tool was investigated. PTFE tubing had been used in chemostat sampling where a stream of carrier gas was passed through it and the effluent analysed, (Mclee and Wayman, 1971). It has not been used previously as a sampling tool in soil atmosphere studies.

Currie discusses the point that adequate aeration in the field is not only a function of biologically active soil depth but also of the structure to be found at a particular depth (Currie, 1961). Thus the composition of the atmosphere within soil crumbs contributes to the aeration status of the soil as a whole.

Clods are formed in the field where soil structure has broken down. In this investigation it was hoped to simulate these clods and to study the soil atmosphere within these structures, over a period of time.

Two types of experiments were set up. In the first a single sampling tool was inserted into a laboratory made clod. In the second an attempt was made to study how the composition of the atmosphere altered from the centre of the clod to the surface exposed to the surrounding air.

CHAPTER 3

MATERIALS AND METHODS

I Soil Atmosphere Studies

To reach the plant, gas must diffuse through air and water-filled pores to the vicinity of the plant roots and then through a moisture film that may surround the plant root. It is the composition of the atmosphere at the root surface that is important to the growth properties of the plant. However, for a given moisture tension, an equally valid measurement is that of the composition in the air-filled pore spaces around the roots. It is this air-filled pore space that is being analysed in the sampling technique employed.

Sampling Probes

The probes used to sample soil atmosphere follow the design of Dowdell et al (Dowdell et al, 1972). Each consist of a porous bronze cup, the pore size of which permits ready entry of gas or water but excludes soil particles. Stainless steel sampling tubes rise from the cup to above the soil surface. Copper tubing was fitted to extend the sampling point to beyond the edge of the plot, so avoiding trampling around the probe. The end of the tubing, the sampling point, was closed with a three-way nylon tap.

Insertion of a probe was by digging a hole with a screw auger to the depth required. The screw auger had the same diameter as the flange of the probe. The probe was placed in this hole and then the space above was tightly packed with sieved air-dried soil. This soil was used so that a tight seal would be achieved on rewetting.

Probes were inserted in each of the no-tillage and ploughed plots in similar sub-plots. The sub-plots were those receiving 100 Kg N per hectare. In each of these sub-plots one probe was inserted to a depth of 15cm, at the

mid-point of the sampling cup, and a second was inserted to a depth of 30cm. (Photographs 1 and 2, Appendix 1)

There were 32 probes, in total, 16 on no-tillage plots, 16 on shallow ploughed plots. Further, as shown in figure 1, Chapter 2, the two blocks of the experiment were each, broadly, of different soil type. Thus with careful placement of the probes half of the probes for each tillage treatment were in the lighter soil, the Macmerry soil series, and half in the Winton soil series.

There were thus four replicates for each of the eight combinations of treatments. This arrangement is shown in the following table.

Siting of soil probes

Cultivation Treatment	Soil Type	Sampling Depth	No. of Probes
No-tillage	Winton	15cm	4
		30cm	4
	Macmerry	15cm	4
		30cm	4
Shallow ploughed	Winton	15cm	4
		30cm	4
	Macmerry	15cm	4
		30cm	4
	Total number of probes		32

Once the probes were in situ they were left undisturbed for the duration of the sampling period.

The probes were inserted after the barley was drilled and left for at least a week before the first sampling date. They were then lifted for harvest and replaced in similar situations after cultivation treatments had been carried out. Again, a period of at least a week was left between re-insertion and the first sampling date of that period. The probes had to

be lifted again before the next season's drilling operations.

Sampling was carried out, at approximately weekly intervals, in the following periods.

Growing Season 1973	:	4th May - 28th August 1973
Winter 1973/74	:	22nd November 1973 - 27th March 1974
Growing Season 1974	:	18th April - 27th August 1974
Winter 1974/75	:	28th January - 1st April 1975

Thus regular sampling of the soil atmosphere was carried out over two complete seasons.

To collect the soil atmosphere samples from the probes $1cm^3$ glass syringes were used. Three-way nylon taps, similar to those at the sampling points of the probes, were fitted to the luer-tip of the syringes. The syringes were prepared by numbering the syringes, greasing the plunger to ensure free movement, and filling the syringes, after preliminary flushing, with nitrogen. These prepared syringes were carried to the field in fitted trays.

In the field the tap on a syringe was fitted into the tap of a sampling point, and held together. (Photograph 3 : Appendix 1.) The tap openings were arranged so that, by depression of the plunger, nitrogen was expelled through the side-arm of the sampling point tap. This procedure flushed the taps. The tap openings were then rearranged so that a sample could be drawn from the sampling point. The first three to five cm^3 drawn up were discarded through the side arm of the sampling point tap. In this way the syringe was flushed. Preliminary experimentation had shown that a sample which analysed consistently could be obtained after this volume had been discarded from the sampling point tubing.

A sample drawn from the sampling point was then stored in the syringe. The taps to both the syringe and sampling point were closed before these taps were disconnected. Four $1cm^3$ samples were drawn from

each sampling probe using separate glass syringes.

The samples so obtained were stored overnight for analysis the following day.

Gas Analysis

Analysis of gas samples was made on a Pye Unicam Model 34 chromatograph fitted with a dual detector arrangement of a Katharometer and a flame ionization detector (Stevens, R.J., pers. comm.) (Photograph 4 : Appendix 1). Two columns were utilized, one packed with Molecular Sieve 5A, and the other with Porapak 'R'. These were held in the one oven at a temperature of 60°C. Helium was used as a carrier gas at a flow rate of 24cm^3/min. The Katharometer was held at a bridge current of 250 mA.

The arrangement was such that each detector had a separate pen recorder. With an injection of a gas sample onto the molecular sieve column separation was effected between nitrogen and oxygen plus argon in the soil atmosphere. The separated gases were detected by the Katharometer and the trace recorded. A correction was employed to take into account the argon contribution to the oxygen peak. This correction was such that the correct oxygen percentage of the unknown was calculated by taking 0.80 from the uncorrected oxygen percentage. Therefore,

Correct oxygen percentage = Uncorrected oxygen percentage - 0.80 (Hamilton and Kory, 1960).

With an injection of a gas sample on the Porapak 'R' column, nitrogen and oxygen with argon were not separated. Adequate separation, however, was achieved between methane, carbon dioxide and ethylene. The effluent from this column passed first through the Katharometer detector and the trace was recorded. The gas stream continued to the flame ionization detector, which was mounted on top of the Katharometer, and the constituents were again detected and the trace recorded by the second pen recorder which was connected to this detector. By this system, those constituents of a sample

which passed through undetected by the Katharometer were detected by the more sensitive flame ionization detector.

Thus, to achieve complete analysis of the soil atmosphere two $1cm^3$ samples were used, one injected on each of the two columns, molecular sieve and Porapak 'R'. This method was used for all gas analysis carried out.

Four $1cm^3$ samples were collected from each sampling probe so that duplicates were available in the case of any error. To inject one of these samples into a column the tap was left attached to the syringe and a disposable needle fitted onto the tap. The tap was then opened after the needle had pierced the injection point of the column.

In order to achieve calibration of the chromatograph three gas mixtures of oxygen, carbon dioxide, ethylene, methane, and nitrogen were used. The accurate composition of these mixtures was known. $1cm^3$ samples of these, in similar syringes, were injected into the columns at intervals throughout the analysis procedure. From the peak heights obtained with the separation of these mixtures used as standards a regression line was calculated for each of the constituents. The composition of unknown samples were then found from these calibration curves.

Water Samples

On occasions water and not air was drawn from the sampling probe. In these cases a missing value was inserted in the subsequent computer analysis of the results obtained from the remaining probes.

A system was developed to deal with water samples in the future. A gas sample had to be obtained from the water sample drawn from the probe. Two $5cm^3$ glass syringes with three-way nylon taps fitted to the luer-tip of the syringes were used to collect the water sample. The $10cm^3$ water sample so collected was stored overnight in these syringes and then subsequently injected into a $\frac{1}{2}$oz bijou bottle which was fitted with a

subaseal cap, and which had been flushed with nitrogen gas. The bottle was shaken for two minutes. Gas was thus displaced from the water into the environment above. The gas was then sampled using $1cm^3$ glass syringes prepared as for field sampling. Two $1cm^3$ samples were collected and these were immediately analysed on the gas chromatograph.

By this method a gas from water sample was obtained and analysed. The peak heights so obtained, were used to derive the composition of soil air in equilibrium with the original water sample.

The factors to be used in this derivation were found by analysing gas from water samples that had been obtained from water in equilibrium with known gas mixtures. To obtain these water samples gas mixtures of known composition were bubbled through water, in sealable bottles on a shaker, for a period of five hours. Gas from water samples were then obtained by the method described. From the peak heights found on subsequent analysis factors were calculated by which the peak heights had to be multiplied to give the composition of the known gas mixture used. Hence the composition of air in equilibrium with the water was calculated.

This system was used in an analysis of the results from the final sampling period, Winter 74/75.

Related data

Data related to the composition of the soil atmosphere, to aid in the interpretation of the results, was also collected.

Soil temperature was recorded by having thermistors attached to twelve of the gas sampling probes at the sampling depth. Probes were selected so that all treatments were covered and these probes were distributed evenly over the area being used in the field. The temperatures were read at the same time each week, using a Grant recorder.

Moisture content data was made available by collecting soil samples, using a screw auger, at the time of gas sampling, at similar depths, and

in the same plots. These were weighed before and after oven drying overnight. From these weighings moisture content, o/o W/W was calculated.

Rainfall figures were available from a nearby meterological station, and bulk density figures were kindly supplied by SIAE (Pidgeon, pers. comm, from SIAE collected data.). At the completion of the sampling period soil samples were taken, representative of all the treatments and these were analysed for organic matter content.

II Flask Analysis

Soil, for analysis in flasks, to monitor the capacity of the soil to produce ethylene was taken from areas in the field that were known to be of the Winton and Macmerry soil types. Further, soil was taken from no-tillage and shallow ploughed plots, and at the two depths studied in the soil atmosphere investigations, 15cm and 30cm. A screw auger was used for soil sampling.

Eight different samples of soil were thus collected, corresponding to the areas in the field studied for soil atmosphere. These samples were as shown below.

	Soil Type	Cultivation Treatment	Depth of sampling
1.	Macmerry	shallow ploughed	15cm
2.	Macmerry	shallow ploughed	30cm
3.	Macmerry	no-tillage	15cm
4.	Macmerry	no-tillage	30cm
5.	Winton	shallow ploughed	15cm
6.	Winton	shallow ploughed	30cm
7.	Winton	no-tillage	15cm
8.	Winton	no-tillage	30cm

Enough soil was collected each month, during 1974, to set up four replicates for each of the above treatments. This soil was air-dried for two - four days. Fifty grams was placed in $50cm^3$ graduated flasks and $25cm^3$

of water added to each. These flasks were then fitted with subaseal caps. The flasks were next flushed with nitrogen by means of two needles inserted in the cap, one connected to a nitrogen gas supply.

The flasks were left for, on average, four weeks and atmosphere samples were taken at intervals during this period by means of inserting a syringe needle into the subaseal cap. These were immediately analysed by the procedure already described.

III Clod Work

Various attempts were made at packing soil to form clods in the laboratory. Most success was achieved with soil that was sieved, then passed twice through a soil shredder which broke down soil crumbs. The soil was then left to air dry when it was passed through the soil shredder again. This resulted in a very fine soil with a minimum of soil crumbs.

The soil had to be rewetted to pack it into metal cylindrical formers to form clods. 27% W/W moisture content was found to achieve a clod that was moist enough to hold together but did not have excess moisture apparent. Rewetting was carried out in a cylindrical former. A known weight of dry soil was packed in and the appropriate volume of water to achieve a moisture content of 27% W/W was sprinkled on this layer of soil. The procedure was repeated until the former was filled.

The cylindrical former which was used was in two halves lengthwise. When in use to form a clod the two halves were bolted together. The bolts were removed after the clod had been formed and the former was then taken off. In this way smearing of the sides of the clod was avoided.

Once constructed the clods were kept at 27% W/W moisture content by means of spraying over the surface of the clod daily the weight of water lost.

Clods were made up with a coiled length of PTFE tubing inserted in them. The PTFE tubing that was used was thin walled electrical sleeving (FTW16, Polypenco Ltd.) with a wall thickness of 0.015cm. The lengths employed

were 195cm long which had an internal volume of $3cm^3$. A length of stainless steel tubing of similar diameter was attached to each end of the PTFE tubing. By this means the interior of the clod could be sampled from an external sampling point. The external sampling points were closed with three-way nylon taps attached to the stainless steel tubing. All of these joints were tested, prior to usage, to ensure that they were air tight.

The second experimental situation was where two such lengths of tubing were inserted into a clod. The arrangement was such that one length of tubing was situated to sample the centre of the clod and the second tubing length was arranged to sample a concentric circle further out along the radius of the clod. By this means it was hoped to study how the composition of the atmosphere altered from the centre of the clod to the surface exposed to the surrounding air. (Photograph 5 : Appendix 1)

On dismantling the clods a note was made of the placing of the PTFE tubing within the dimensions of the clod.

To confirm that the PTFE tubing was porous and hence to confirm its suitability as a sampling tube 195cm lengths of the tubing were filled with a gas mixture of known composition. These lengths of tubing thus had an internal volume of $3cm^3$. The ends of the tubing were closed with nylon taps. Every hour for a period of six hours a $1cm^3$ sample of the gas inside a length of tubing was collected and then analysed. A length of tubing that had not previously been sampled was used. This test was repeated using gas mixtures of different known composition.

If the tubing was porous a change in composition of the internal environment with time should be seen.

For all clod work the soil that was used was of the Winton soil type.

From available data, i.e. weight and dimensions of clods, the bulk density of each clod made was calculated.

CHAPTER 4

RESULTS

I Soil Atmosphere Studies.

Sampling Probes.

Graphs are presented of the results obtained from routine sampling of soil atmosphere from the probes.

Figures 1 to 6 show the mean of all thirty-two sampling probes on each sampling date for gases analysed from the soil atmosphere sample. These graphs show mean carbon dioxide percentage, oxygen percentage, and methane ppm plotted against sampling date.

The level of carbon dioxide found in the soil atmosphere was very different in the two growing seasons (Fig. 1 and 2). All recordings, after the beginning of June, were higher in the first growing season than any made in the second. In both years the carbon dioxide percentage of the soil atmosphere rose during the growing seasons until about the middle of July when it began to decline. Comparing carbon dioxide recordings made over the winter periods, except for the beginning of the 1974/75 winter, the levels are very similar.

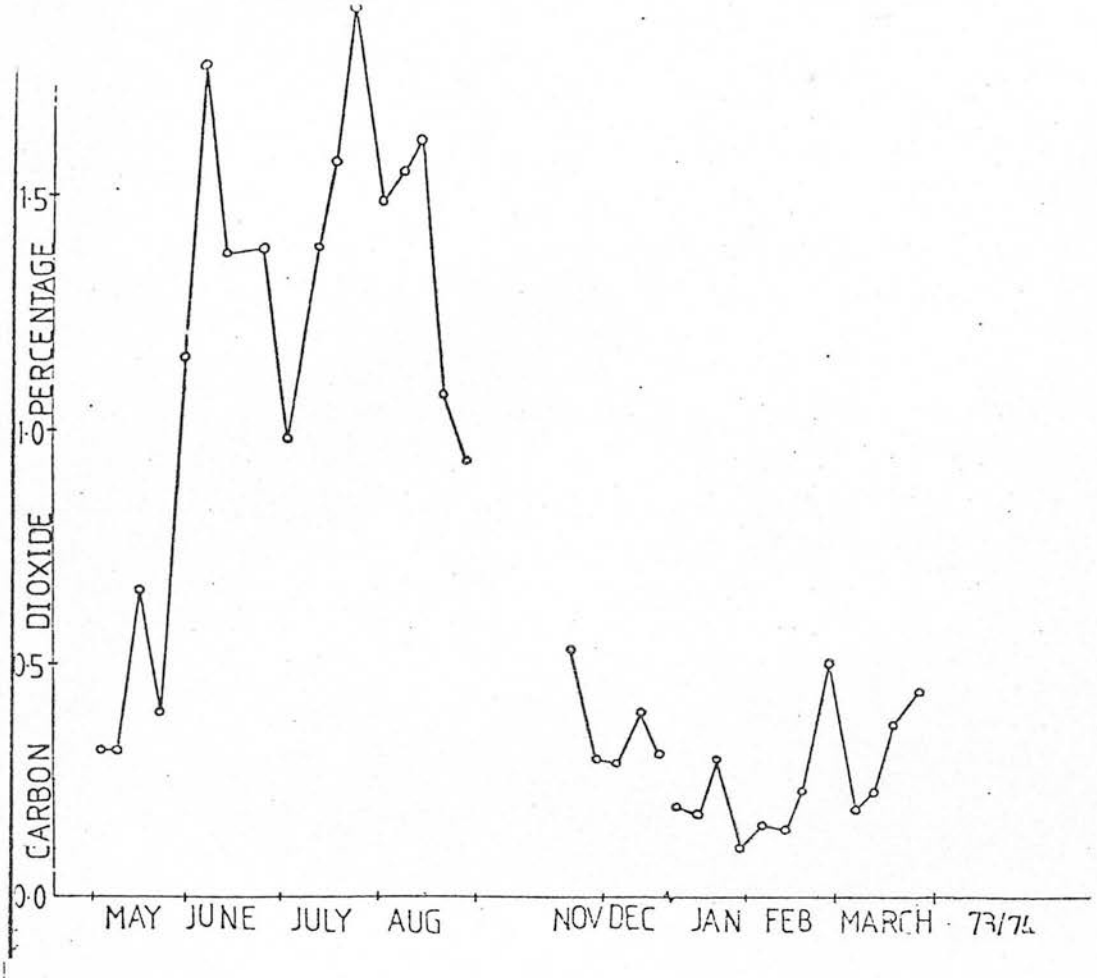
Similarly with the oxygen percentage (Fig. 3 and 4) a difference was observed only in the growing seasons with the oxygen percentage in 1973, being generally lower than in 1974.

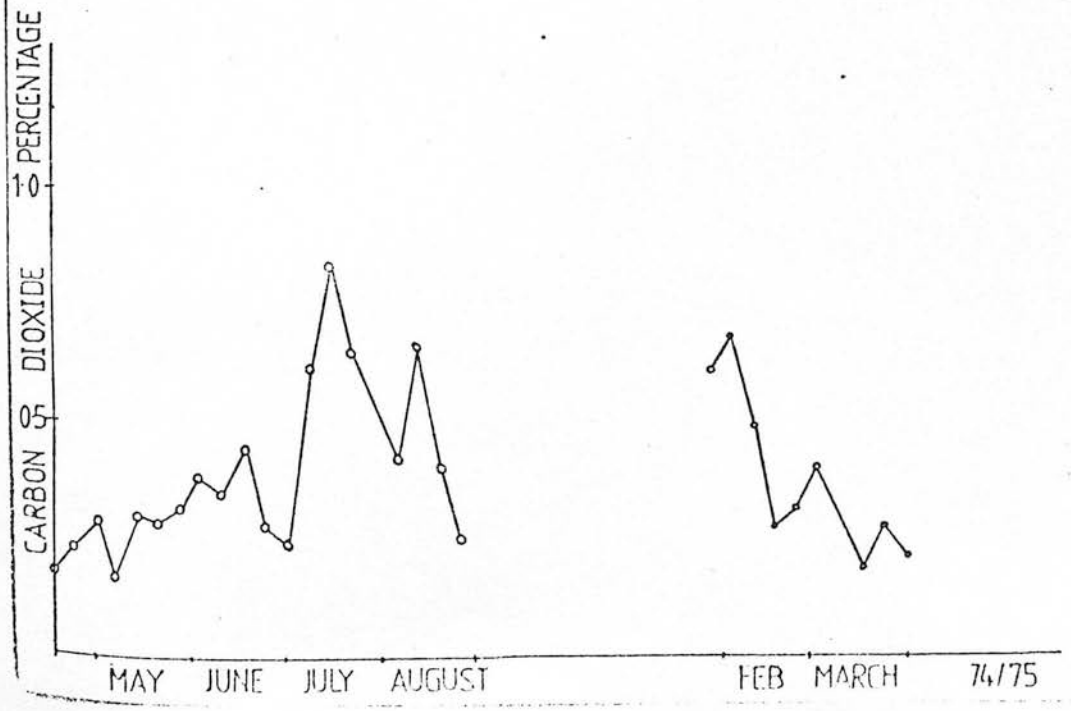
The methane component of the soil atmosphere steadily declined throughout each growing season but levels in the growing season of 1974 were higher than those recorded in 1973. Levels of methane were similar in both winter sampling periods (Fig. 5 and 6).

Table 1 shows the dates on which ethylene was detected in the analysis of soil atmosphere samples and the number of probes in which detection was made. A mean of ethylene ppm has been calculated for these probes and also a mean of the thirty-two sampling probes (Fig. 7 and 8). This data does not include any water samples.

Figures 1 and 2

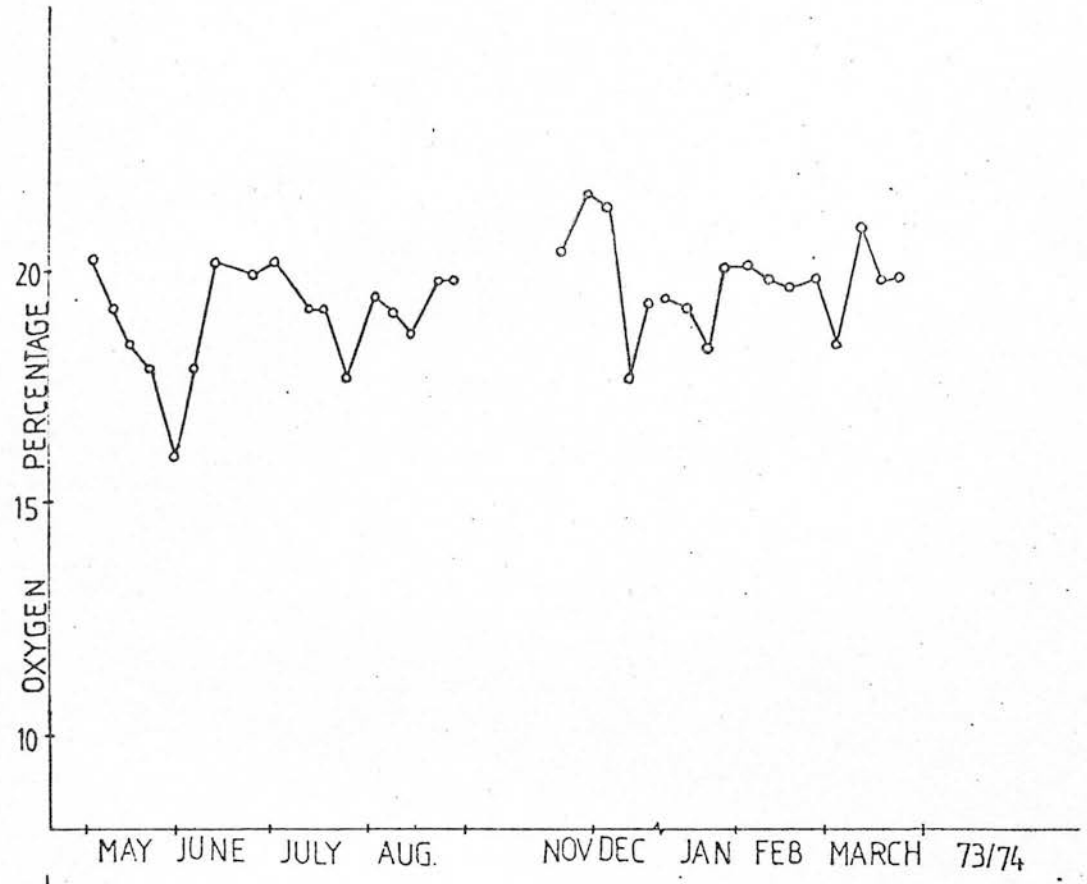
The mean percentage of carbon dioxide in the soil atmosphere for each sampling date 1973-4 and 1974-5.

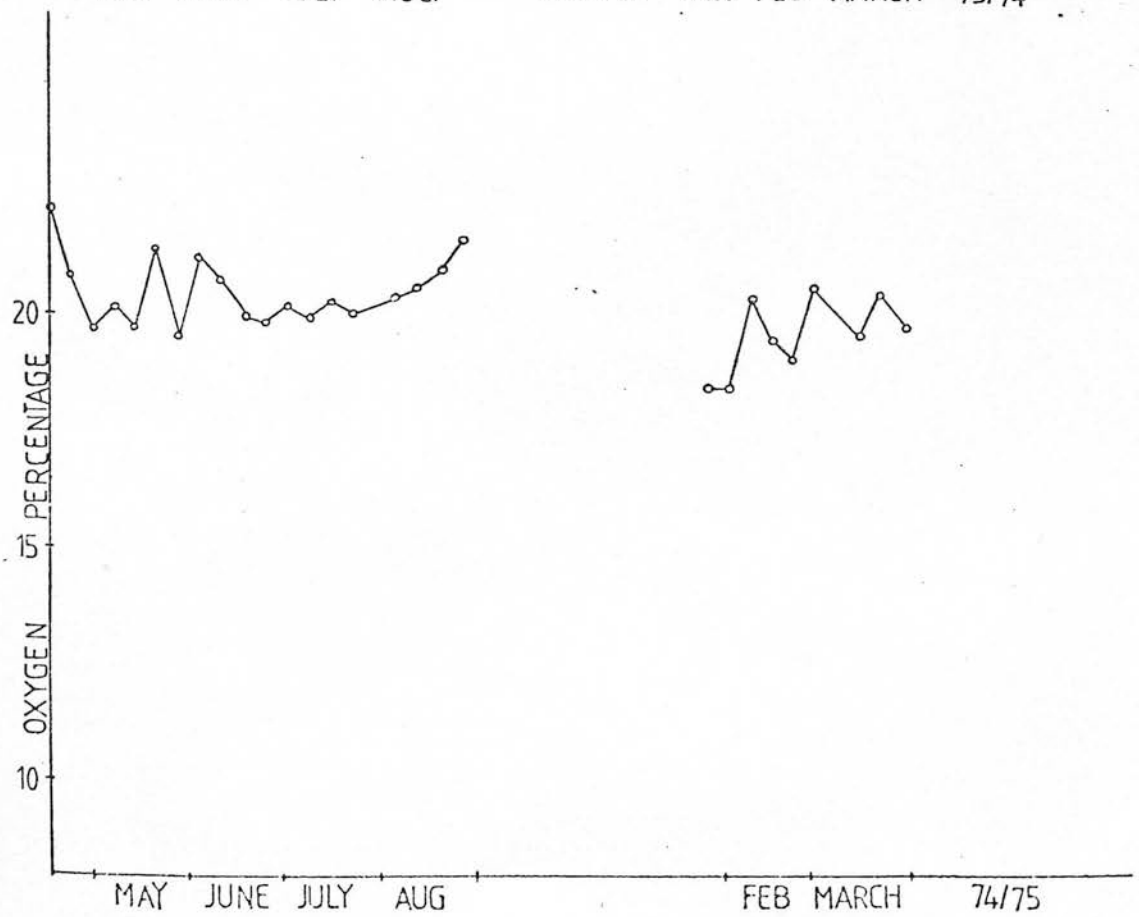




Figures 3 and 4

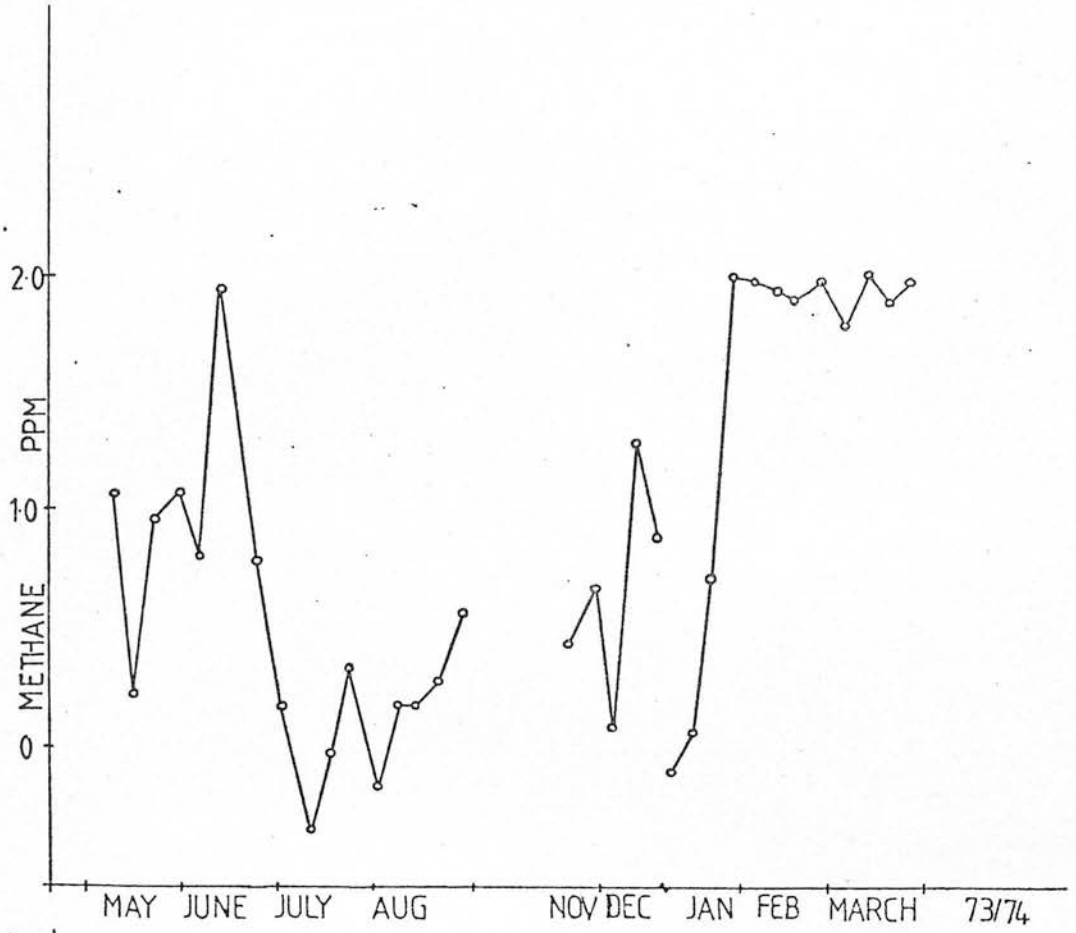
The mean percentage of oxygen in the soil atmosphere for each sampling date 1973-4 and 1974-5.

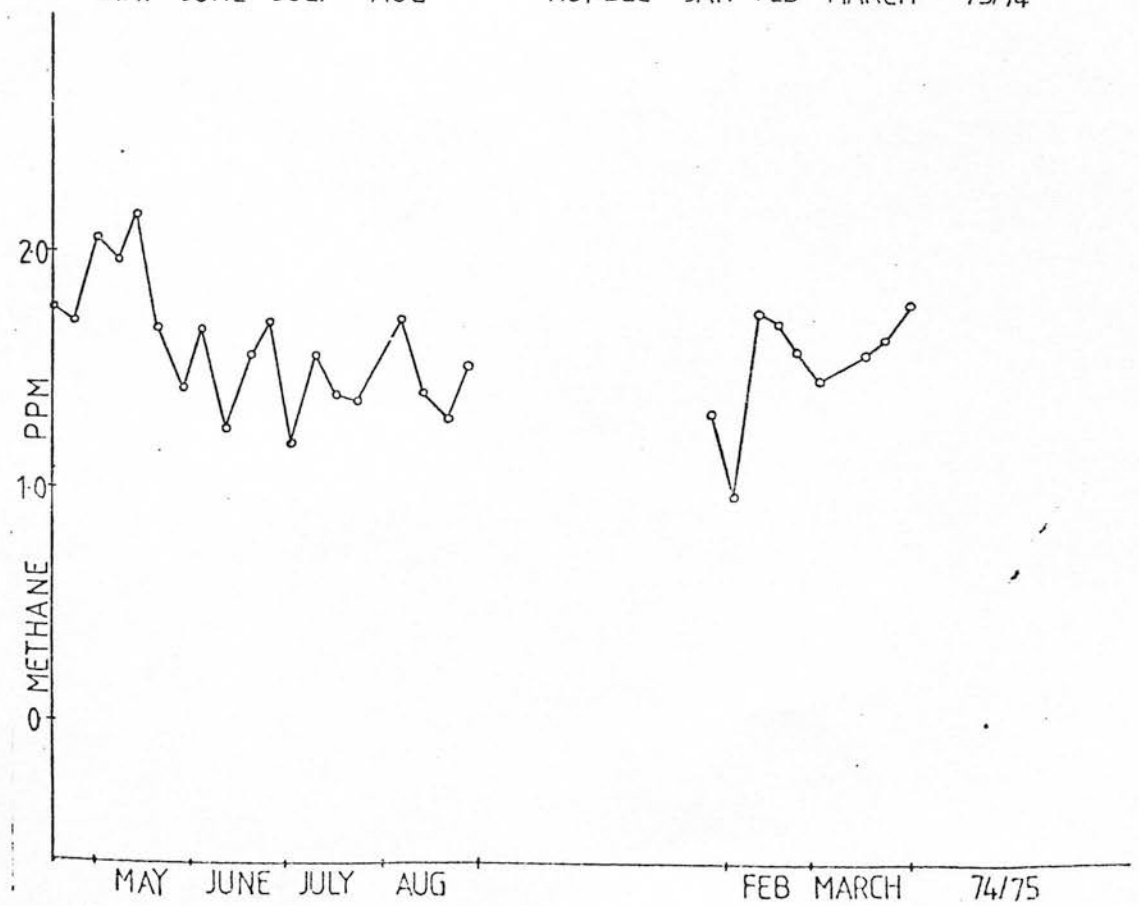




Figures 5 and 6

The mean ppm of methane in the soil atmosphere for each sampling date 1973-4 and 1974-5.





On all but the very first sampling date ethylene was found from at least one probe but on only seven sampling dates in the growing season, and nine in the winter of the first year was ethylene found in more than ten percent of the thirty-two sampling probes. In the second year ethylene was found in more than ten percent of the probes on thirteen occasions in the growing season and on all dates in the winter (Table 1).

The negative figures for ethylene are a factor of the calibration curve used. This was a straight line which did not pass through the origin. Only when a peak was seen on the chromatograph in the position for ethylene was the calibration curve used and hence, although ethylene was therefore present in the soil atmosphere, the error in the system sometimes gave this to be negative ppm.

There is little variation in the overall mean of ethylene in the soil atmosphere except for a peak in early May 1974 (Figures 7 and 8).

Water Samples

Table 2 shows the incidence of water only being withdrawn from the sampling probes. Where no gas analysis results were available missing values were calculated and inserted to complete the data used for statistical analysis.

The incidence of water samples was confined to a few probes only and the majority of these were in no-tillage plots and at the lower sampling depth of 30 cm. Further, 80% of the water samples were in the heavier of the two soil types, the Winton soil series.

A system was developed whereby a gas sample could be obtained from a water sample drawn from a probe. From the subsequent analysis of this gas sample the composition of soil air in equilibrium with the original water sample could be derived. This system was used in an analysis of the results from the final sampling period, Winter 1974/75. The data was also analysed using missing values in places where soil air was not analysed directly, to make it comparable with previous sampling periods.

Table 1. Dates on which ethylene was detected.

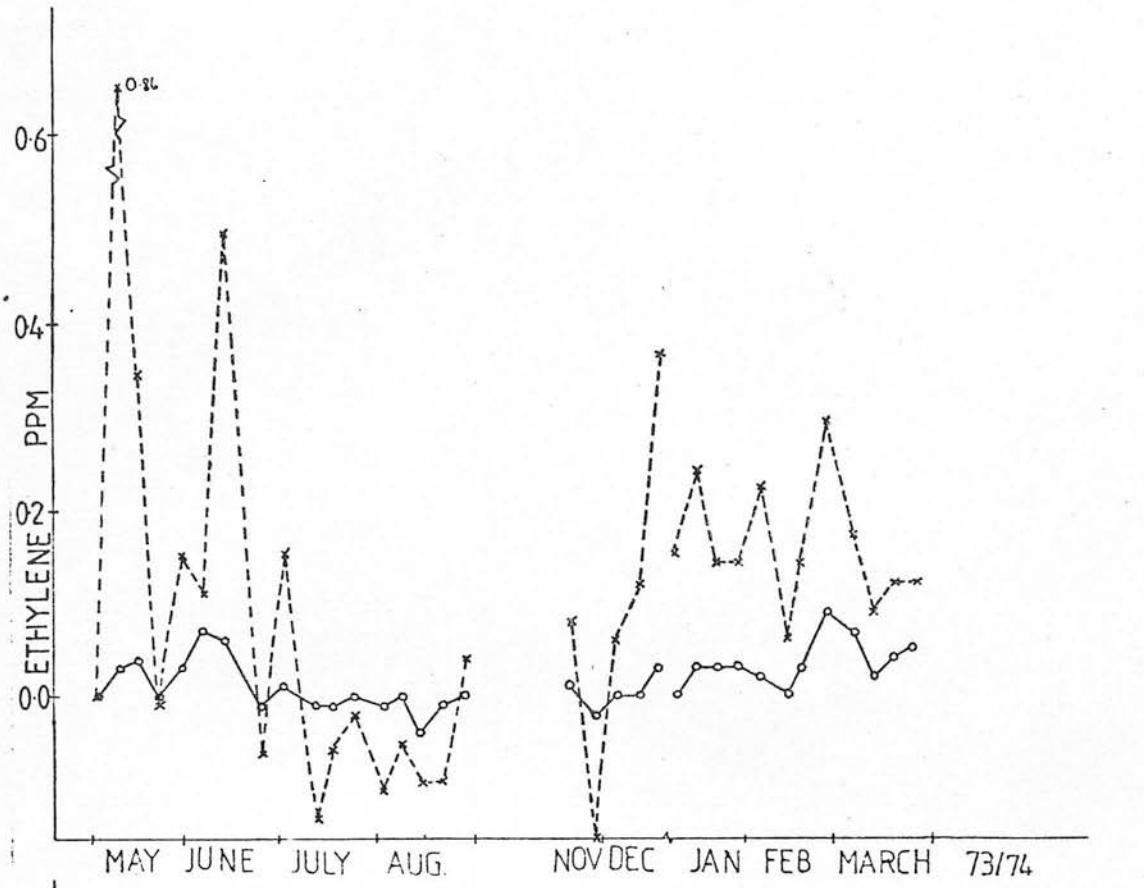
Sampling date	Number of probes giving ethylene	Ethylene PPM. Mean of probes giving ethylene	Ethylene PPM. Mean of all 32 probes
A. Growing Season 1973.			
4th May	0	0.00	0.00
10th ..	1	0.86	0.03
16th ..	4	0.34	0.04
23rd ..	3	-0.01	0.00
30th ..	7	0.15	0.03
6th June	19	0.11	0.07
13th ..	4	0.49	0.06
25th ..	6	-0.06	-0.01
2nd July	3	0.15	0.01
12th ..	3	-0.13	-0.01
18th ..	3	-0.06	-0.01
24th ..	7	-0.02	0.00
2nd August	3	-0.10	-0.01
8th ..	3	-0.05	0.00
14th ..	13	-0.09	-0.04
21st ..	2	-0.09	-0.01
28th ..	3	0.04	0.00
B. Winter 1973/74			
21st November	3	0.08	0.01
29th ..	3	-0.16	-0.02
5th December	1	0.06	0.00
13th ..	1	0.12	0.00
19th ..	3	0.36	0.03
10th January	1	0.15	0.00
17th ..	4	0.24	0.03
23rd ..	8	0.14	0.03
30th ..	6	0.14	0.03
6th February	3	0.22	0.02
14th ..	1	0.06	0.00
19th ..	7	0.14	0.03
27th ..	10	0.29	0.09
7th March	13	0.17	0.07
14th ..	7	0.09	0.02
20th ..	11	0.12	0.04
27th ..	13	0.12	0.05

Table 1. (continued)

Sampling date	Number of probes giving ethylene	Ethylene PPM. Mean of probes giving ethylene	Ethylene PPM. Mean of all 32 probes
C. Growing Season 1974.			
18th April	12	0.01	0.00
25th ..	15	0.05	0.02
2nd May	18	0.29	0.16
9th ..	20	0.27	0.17
15th ..	22	0.10	0.07
22nd ..	12	0.21	0.08
29th ..	11	-0.01	0.00
5th June	11	0.03	0.01
12th ..	12	0.03	0.01
20th ..	7	-0.01	0.00
26th ..	19	0.09	0.05
3rd July	3	0.10	0.01
10th ..	1	-0.13	0.00
17th ..	5	0.09	0.01
24th ..	13	0.11	0.04
7th August	1	0.14	0.00
14th ..	2	0.06	0.00
21st ..	1	0.10	0.00
27th ..	3	-0.09	-0.01
D. Winter 74/75.			
28th January	10	0.27	0.08
4th February	19	0.14	0.08
11th ..	10	0.22	0.07
18th ..	10	0.07	0.02
25th ..	18	-0.05	-0.03
4th March	12	0.12	0.05
18th ..	9	0.05	0.01
25th ..	9	0.11	0.03
1st April	16	0.03	0.02

Figures 7 and 8

The mean ppm of ethylene for those probes in which ethylene was detected (x- - -) and an overall mean for all probes (o——) for each sampling date 1973-4 and 1974-5.



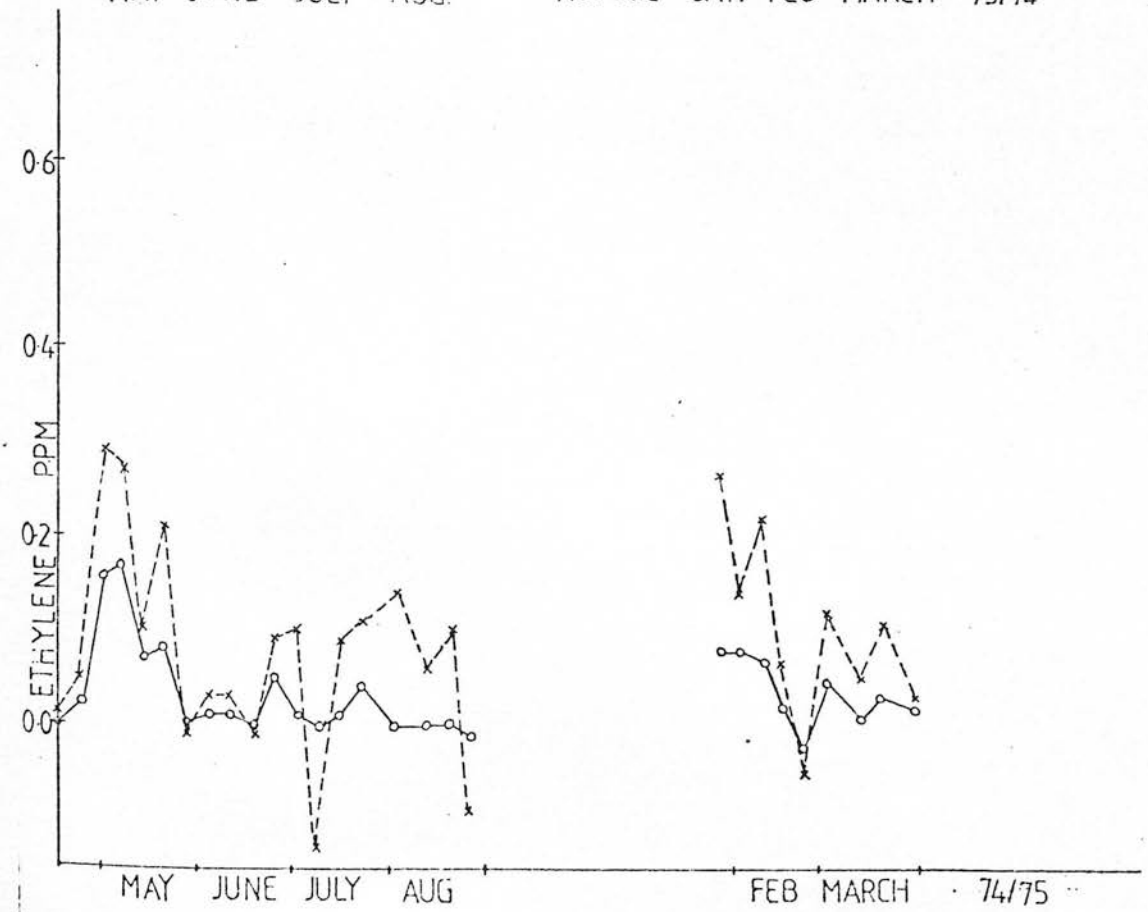


Table 2

The incidence of water samples

Sampling date	Number of probes giving water samples only.	Sampling date	Number of probes giving water samples only
A. Growing Season 1973.		B. Winter 1973/74.	
2. 10th May	3	4. 13th December	3
3. 16th ..	3	5. 19th ..	2
4. 23rd ..	2	6. 10th January	1
5. 30th ..	5	9. 30th ..	1
6. 6th June	1	13. 27th February	1
		14. 7th March	1
		15. 14th ..	2
		16. 20th ..	2
C. Growing Season 1974.		D. Winter 1974/75.	
5. 15th May	1	1. 28th January	7
		2. 4th February	6
		3. 11th ..	1
		4. 18th ..	6
		5. 25th ..	1
		6. 4th March	1
		8. 25th ..	1

The factors calculated to derive the composition of soil air in equilibrium with the original water sample were as follows:-

Carbon dioxide	2.46
Ethylene	9.85
Oxygen	24.17

The peak heights obtained on analysis of the gas sample obtained from a water sample were multiplied by the factor given above to give a peak height representative of the soil air in equilibrium with the original water sample. The results for methane were very variable and hence a factor was not used and missing values were calculated to complete the data.

It was felt that the method needed refinement particularly in relation to leakages. This was highlighted in calculations of oxygen percentages. In many cases, the calculations resulted in oxygen percentages in excess of 21 per cent for air in equilibrium with the water in the soil. Because of the very low solubility of oxygen in water, a small leakage somewhere in the system for converting water to air samples, could easily lead to large discrepancies.

Results are given, therefore, of carbon dioxide percentage and ethylene ppm for this sampling period. These results are presented in Figure 9 as overall means of carbon dioxide percentage and ethylene ppm against sampling date. Figure 10 shows the results obtained from those probes sited in the no-tillage plots, at the lower sampling depth of 30 cm and in the heavier of the two soils, Winton. It is in this treatment that the majority of the water samples were encountered.

Figures 9 and 10 show that in the Winton no-tillage plots at the lower sampling depth both the carbon dioxide percentage and the ethylene component of the soil atmosphere was generally higher than the overall mean.

Figure 9

The mean of carbon dioxide percentage and ethylene ppm against sampling date for the winter 74/75 sampling period. The data includes water samples from which gas samples were obtained (see text).

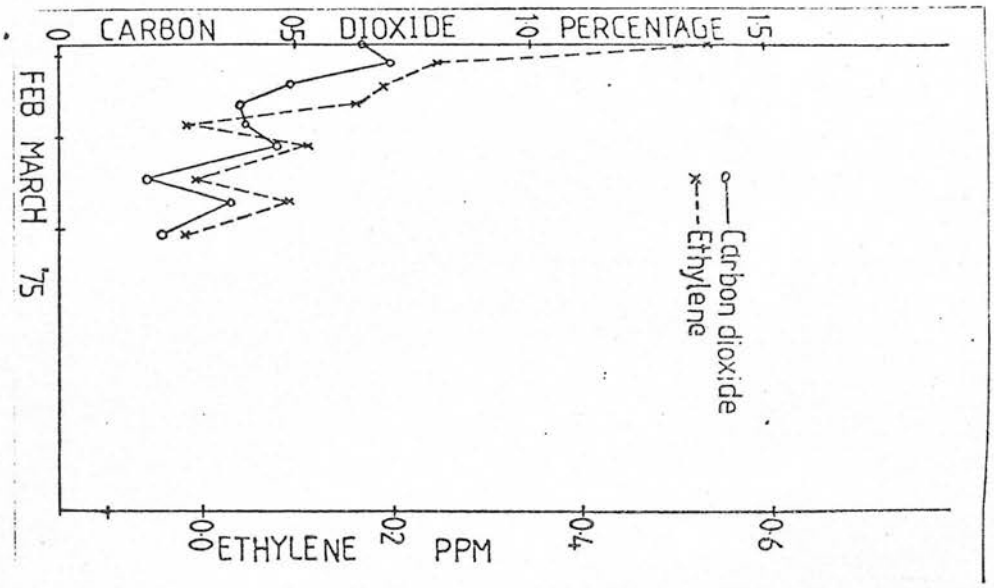
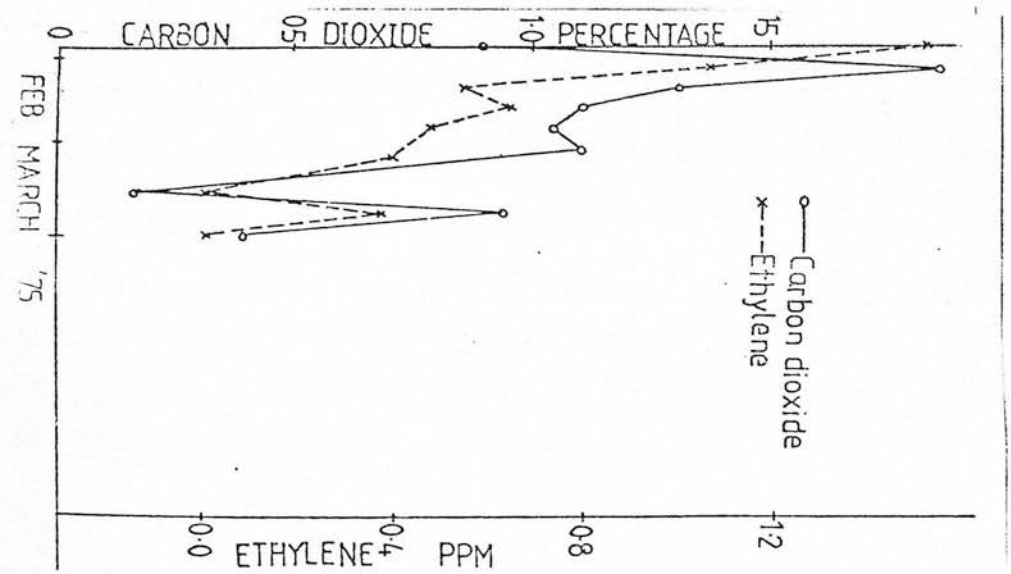


Figure 10

Ethylene and carbon dioxide means for winter 74/75 at 30 cm depth in no-tillage plots of Winton soil.



Related Data

Data collected to aid the interpretation of soil atmosphere results included soil temperature. Thermistors were attached to gas sampling probes representing all treatments. This data, as a mean of the recordings made each week, is shown in figures 11 and 12.

The soil temperature at the beginning of the 1974 growing season was higher than in the first year. However, after early June the situation was reversed with a higher soil temperature being recorded in the first year. In both years soil temperature during the growing season rose up to the beginning of June and then fluctuated around a mean. Winter soil temperatures were very similar each year.

Figures 13 and 14 similarly show the means of the moisture content recordings, on a percentage weight per weight basis, against sampling date. For most of the 1973 growing season the soil was more moist than the subsequent year and winter soil moisture recordings were fairly similar in both years. Soil samples for moisture content were taken from the same plots as used for gas sampling and at similar depths, 15 cm and 30 cm.

Rainfall data is presented as totals for the seven day period prior to each soil atmosphere sampling date (figures 15 and 16). Where a trace of rain was recorded in the meterological log book it was considered to be 0.0mm rain. This data again shows that the growing season of '73 was wetter.

Soil bulk density results were used to calculate air filled porosity from moisture content recorded on a percentage weight per weight basis. The following are the steps in the calculation:-

Air Filled Porosity = Total Pore Space - Moisture Content %V/V

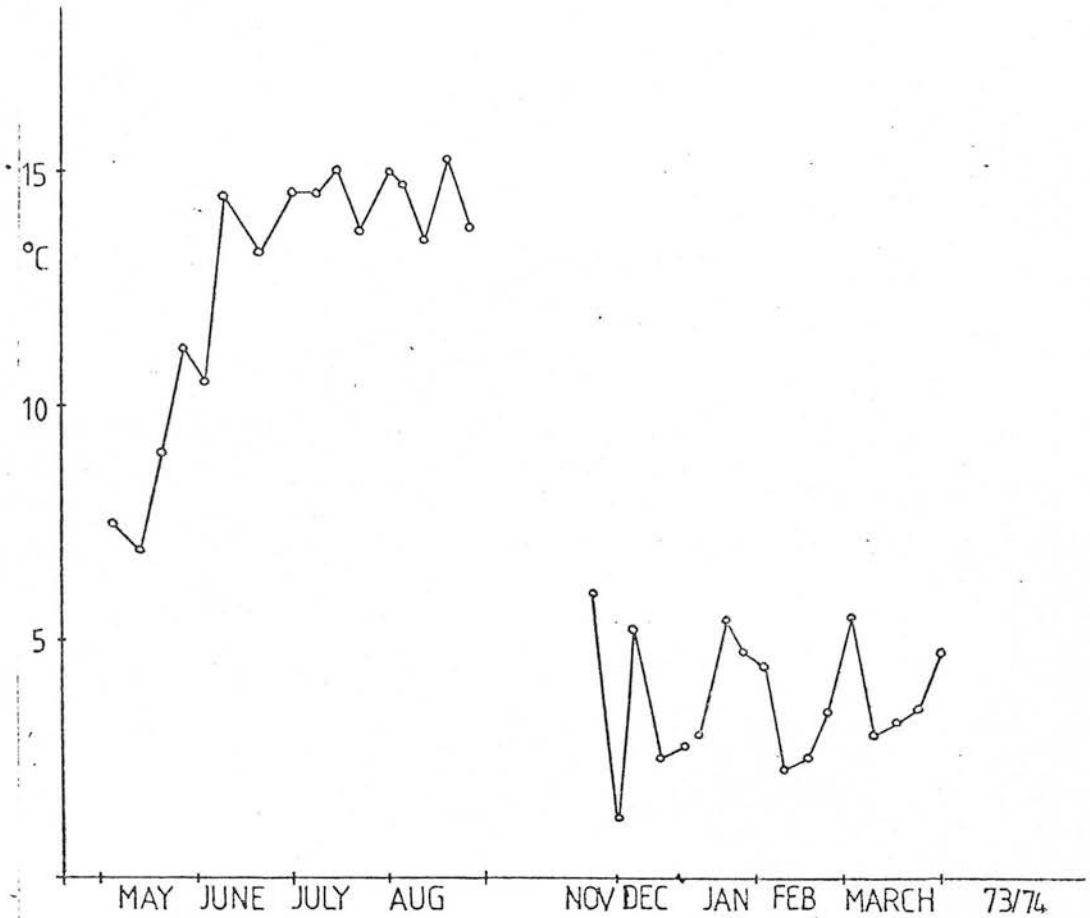
Moisture content %V/V = Moisture content %W/W x Bulk density

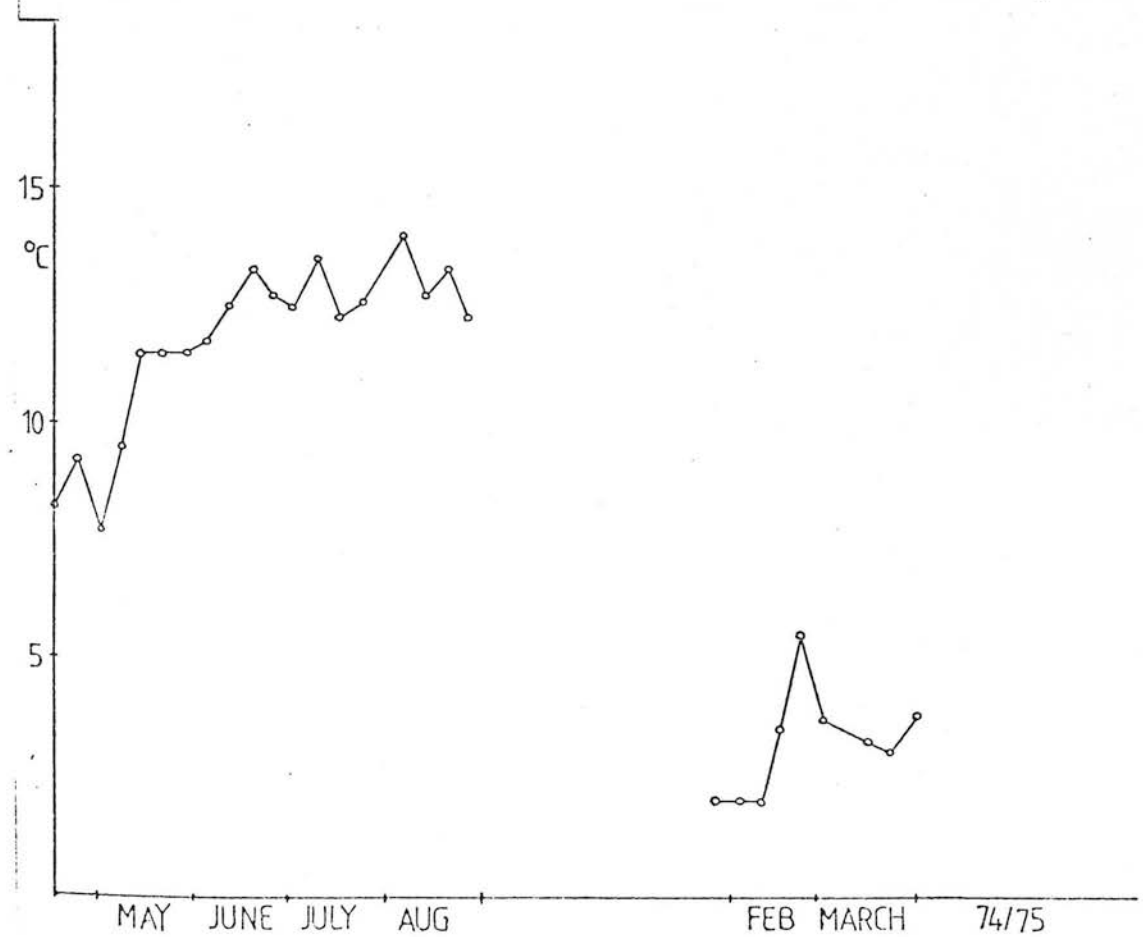
and

$$\text{Total Pore Space} = \left(1 - \frac{\text{Bulk density}}{\text{Particle density}}\right) \times 100\ \%.$$

Figures 11 and 12

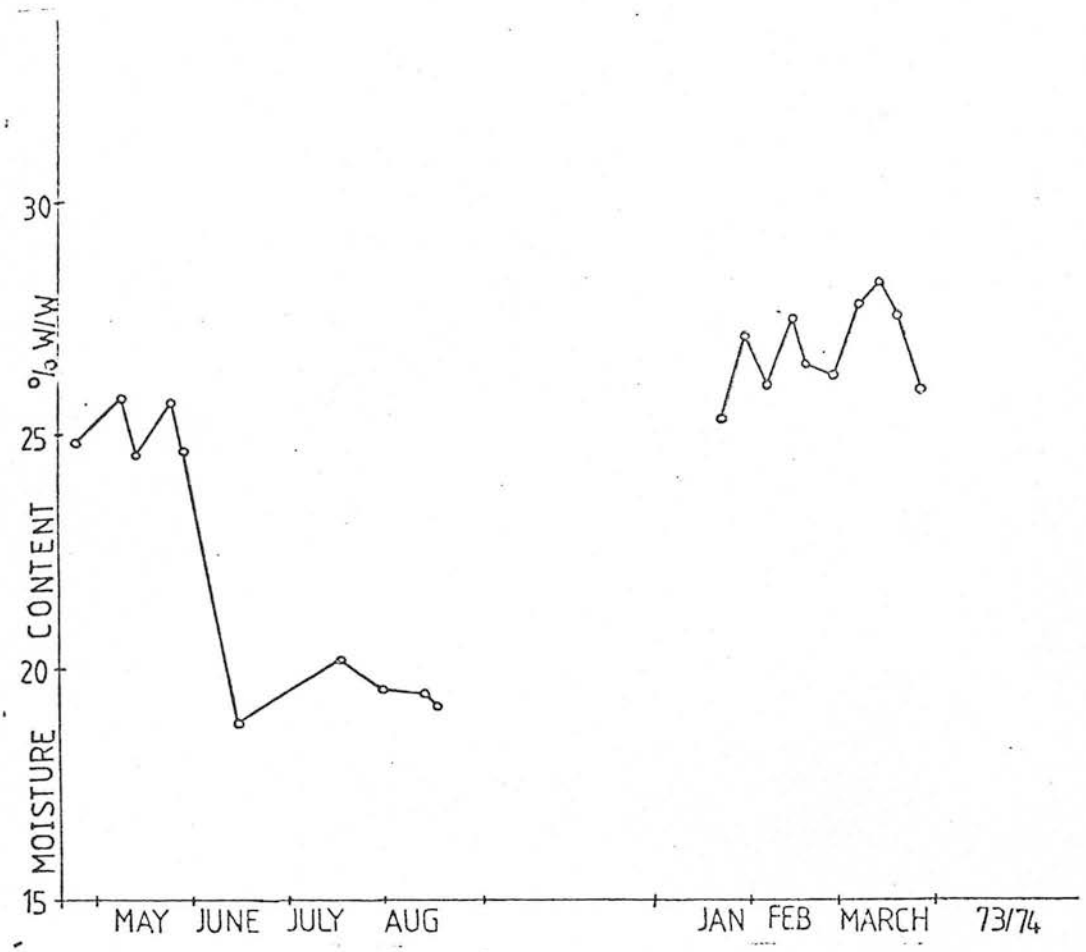
Mean of soil temperature at 9.00 a.m. for each sampling date, 1973-4 and 1974-5.

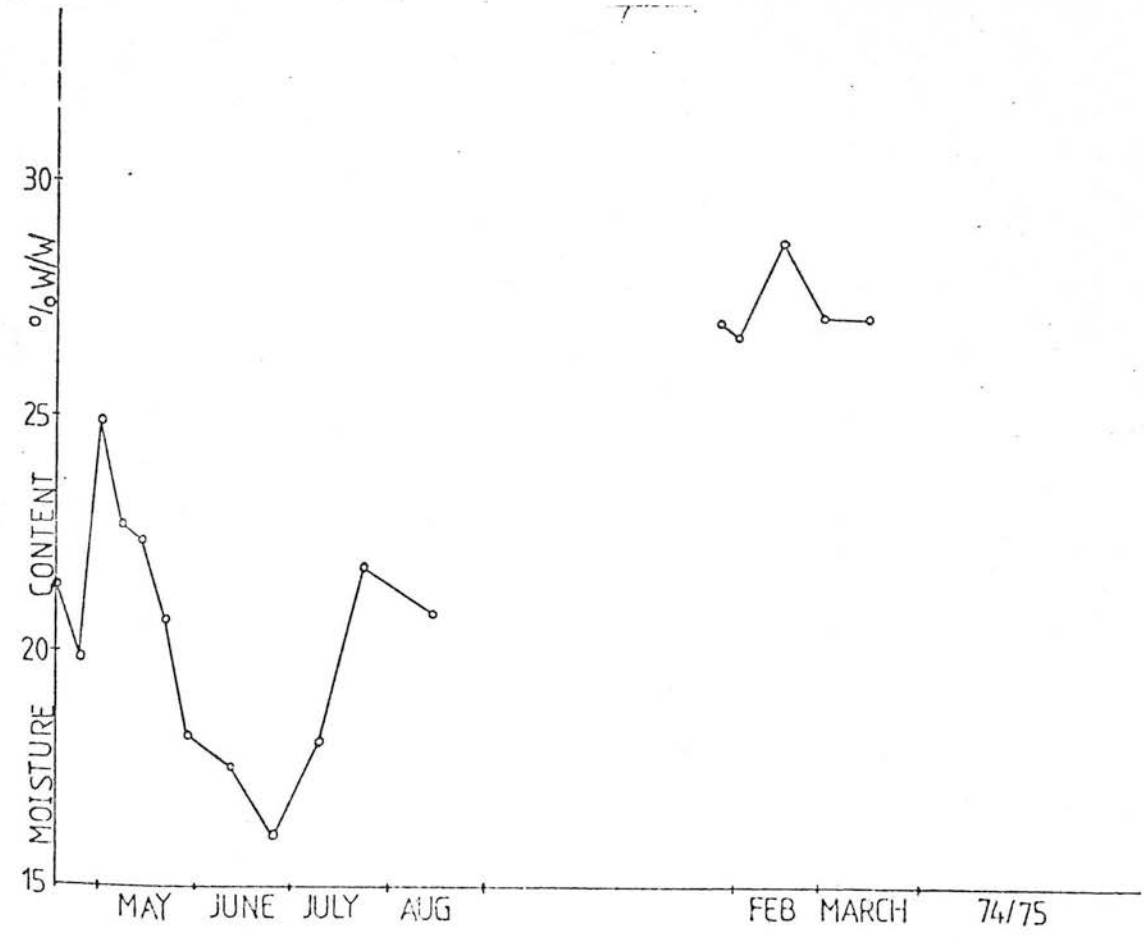




Figures 13 and 14

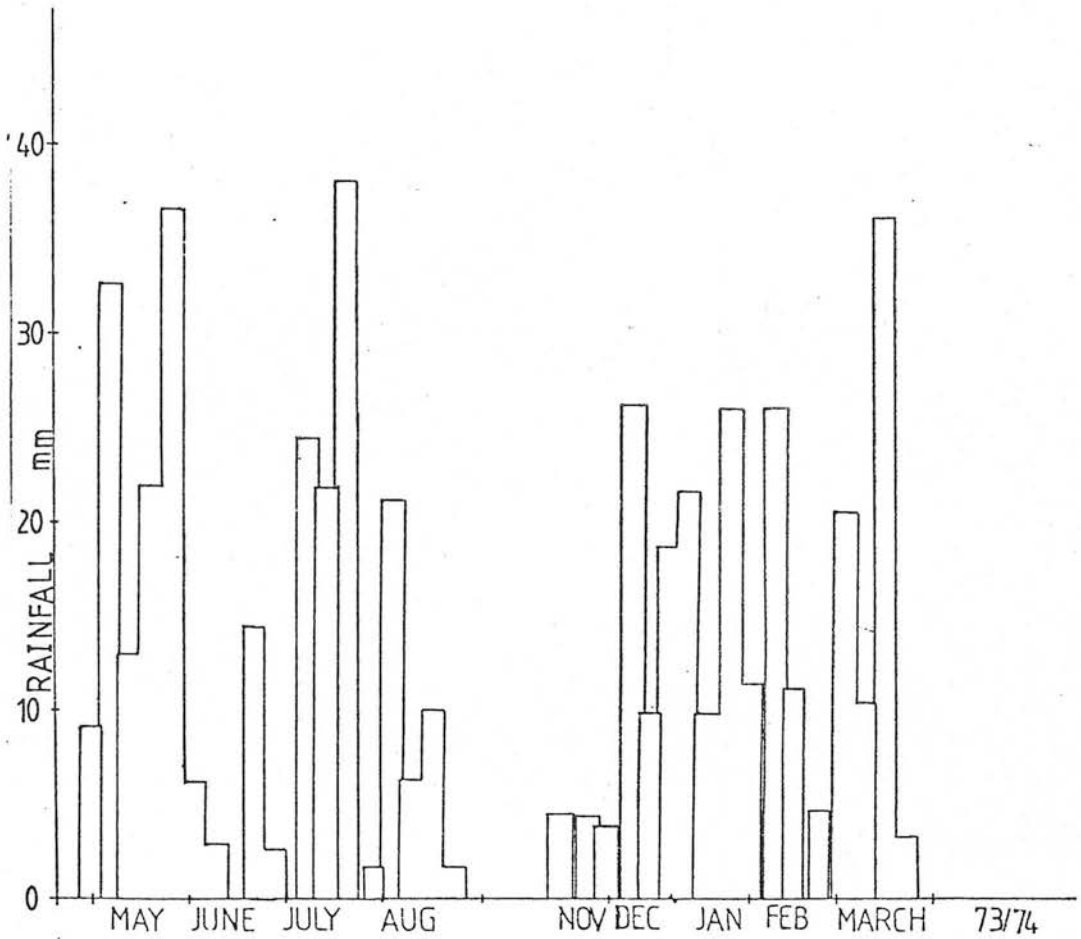
Mean moisture content %W/W from soil samples taken on the sampling dates shown. 1973-4 and 1974-5.

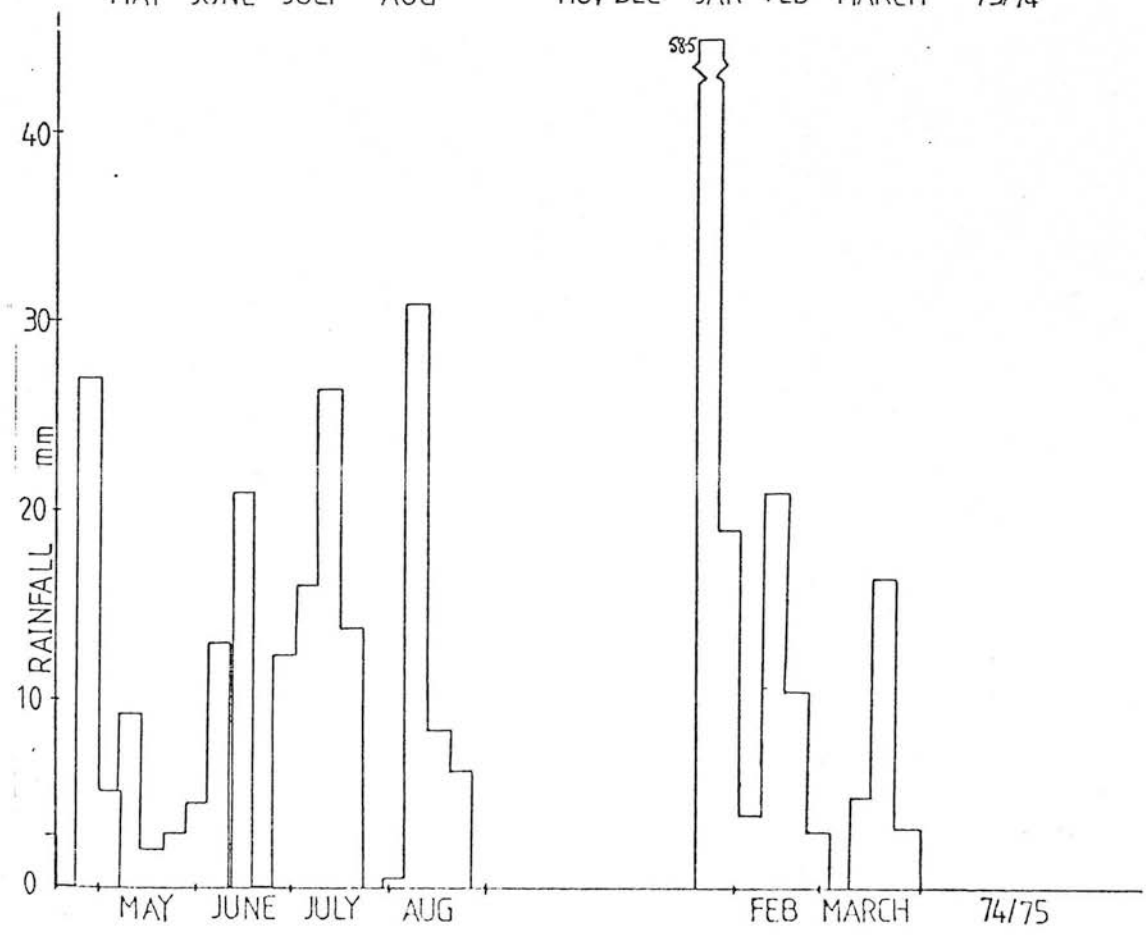




Figures 15 and 16

Total rainfall for the seven day period prior to each soil atmosphere sampling date, 1973-4 and 1974-5.





Particle density has been measured on the site studied and the figure of 2.56g/cm^3 was used. (Pidgeon, unpubl. data).

Measurements of soil bulk density indicate that there was little change for any of the individual treatments during the growing seasons (Pidgeon and Soane, 1977). Therefore, for bulk density, a mean of the '73 and '74 growing season figures recorded at 15 cm and 30 cm was used. This was to minimize the effect of instrument variability. The figures shown below were used in calculations with growing season data.

Treatment Mean		Dry bulk density g/cm^3.
	Overall	1.41
Depth:	15 cm	1.30
	30 cm	1.52
Cultivation:	Shallow ploughed	1.38
	No-tillage	1.45
Soil Type:	Macmerry	1.35
	Winton	1.48

For calculations involving winter data, the dry bulk density figures recorded during the growing season could be used for calculations with data from no-tillage plots. The assumption was made that dry bulk density did not appreciably change in the winter on these plots. However the same assumption could not be made for the shallow ploughed plots. On only one occasion were recordings of bulk density made after ploughing and before secondary cultivations (Pidgeon, 1975). The dry bulk density figures for shallow ploughed plots from this recording were used to give the following table of means used in the calculations of air filled porosity during the winter sampling period.

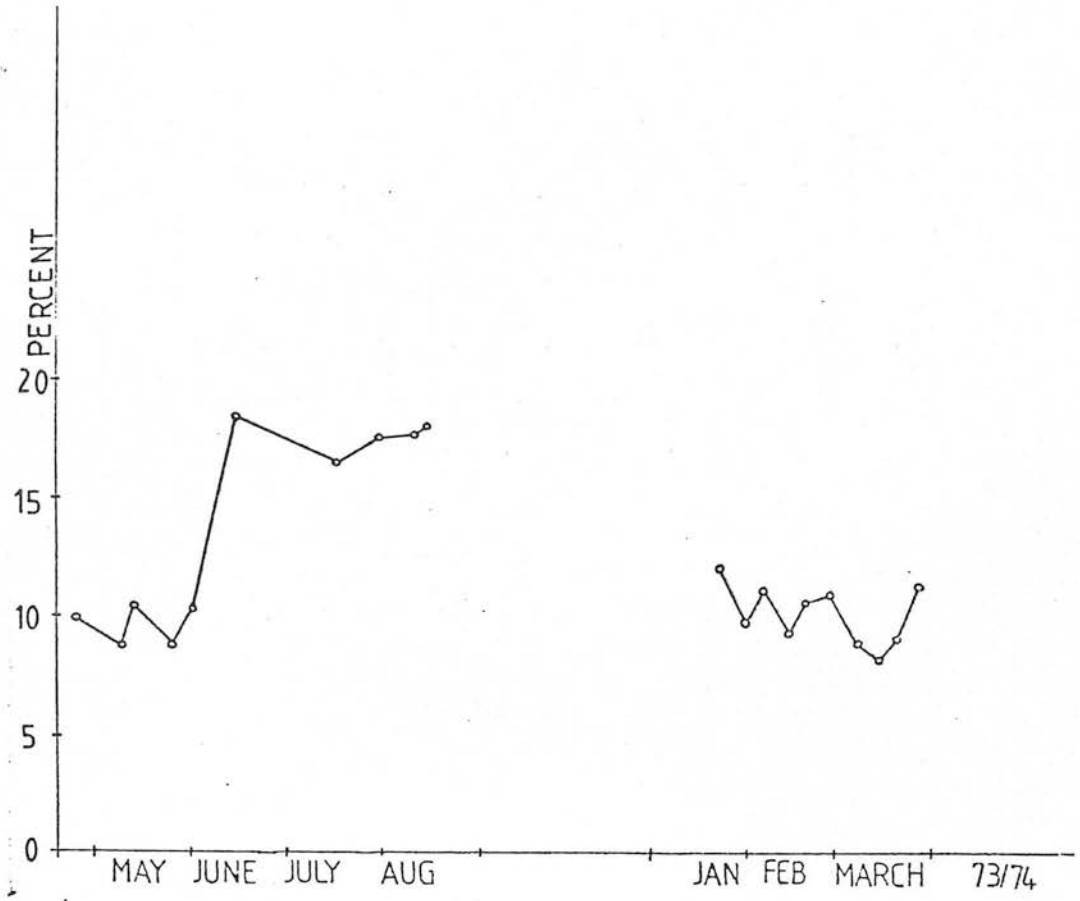
Treatment Mean		Dry bulk density g/cm^3.
	Overall	1.37
Depth:	15 cm	1.17
	30 cm	1.57
Cultivation:	Shallow ploughed	1.29
	No-tillage	1.45
Soil Type:	Macmerry	1.32
	Winton	1.42

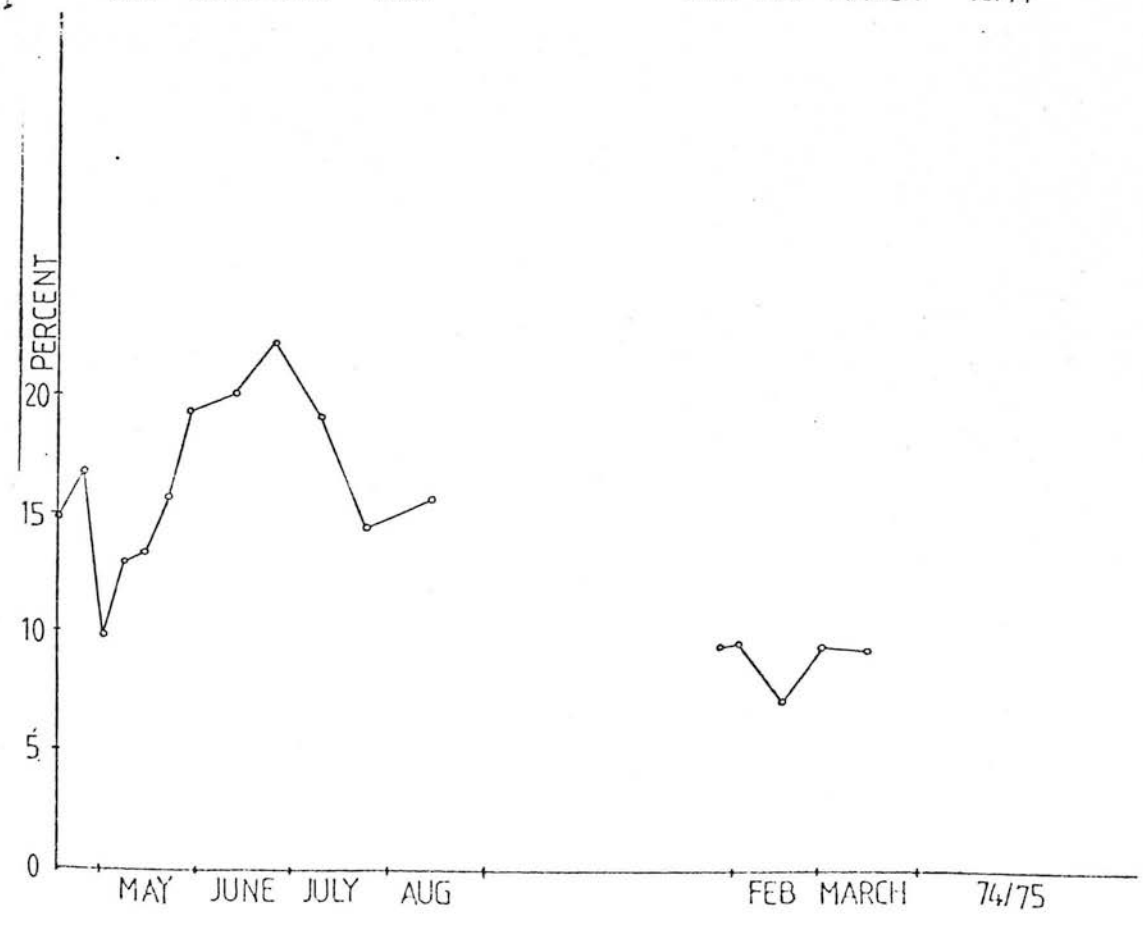
The air filled porosity results so obtained are presented in figures 17 and 18 which show the mean for each sampling date on which soil moisture content was measured. These figures show air filled porosity to be lower for most of the first growing season and little difference to be recorded in the winters of each year. Figures 19 to 24 show the air filled porosity data in such a way as to compare treatments. Figures 19 and 20 show the air filled porosity at the two depths of sampling, 15 cm and 30 cm, figures 21 and 22 compare the air filled porosity of the ploughed and no-tillage treatments and figures 23 and 24 this property of the two soil types. The air filled porosity was lower at 30 cm than at 15 cm especially during the winter sampling periods when at 30 cm the air filled porosity was calculated to be zero on most sampling dates. Comparing the two cultivation treatments, on each sampling date the air filled porosity of the no-tillage plots was lower than that of the ploughed plots and similarly, on each sampling date, the air filled porosity of the Winton soil was lower than that of the Macmerry.

At the end of the soil atmosphere investigation the soil was sampled to find the percentage organic matter. The results were obtained by the Tinsley method for organic carbon (Bremner and Jenkinson, 1960) and then the organic matter calculated by multiplying organic carbon by 1.724. Each plot was sampled at three depths, 0 to 5 cm, 5 to 20 cm and 20 to 35 cm. Table 3 gives these results.

Figures 17 and 18

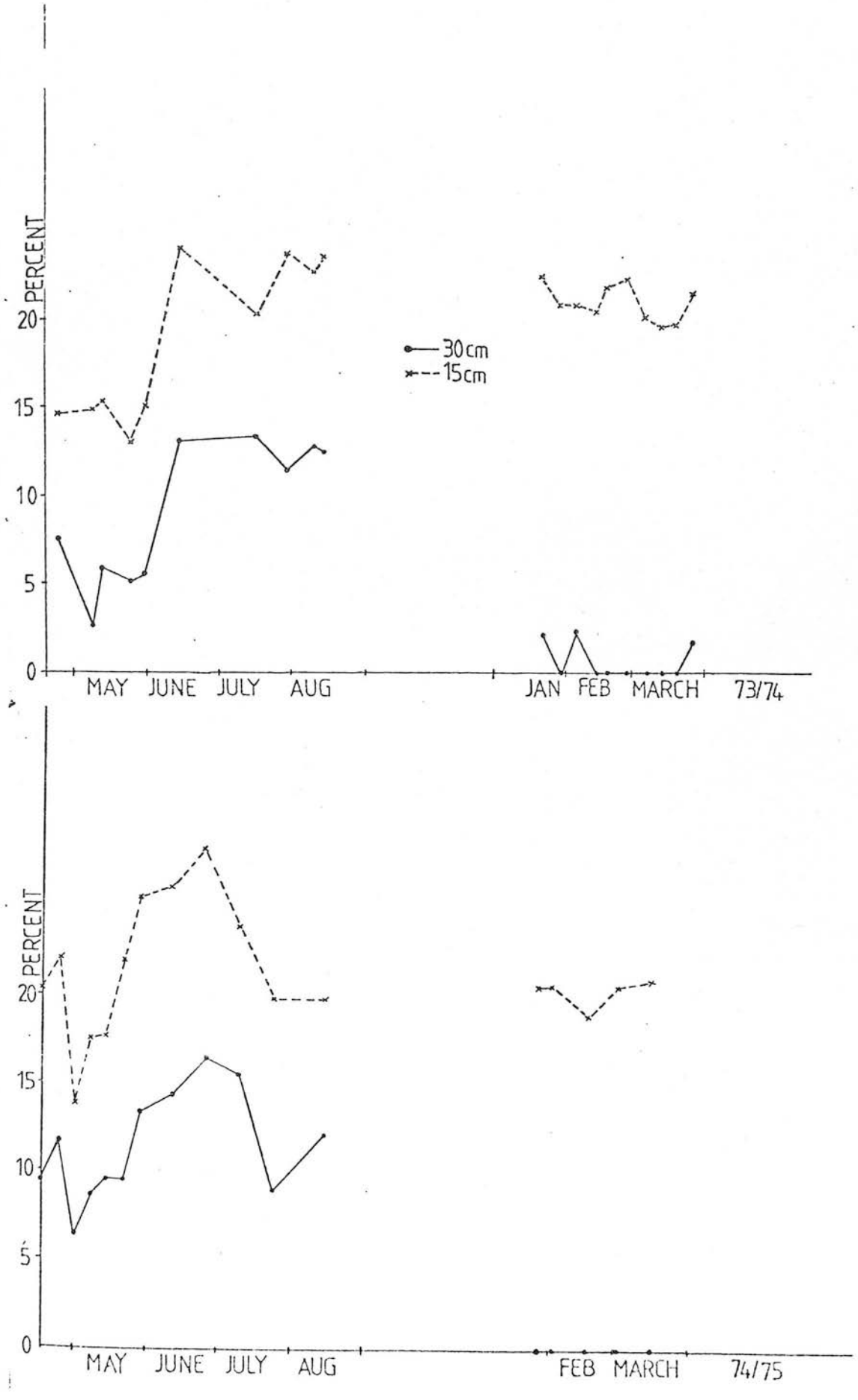
Mean of air filled porosity figures calculated from soil moisture content readings, 1973-4 and 1974-5.





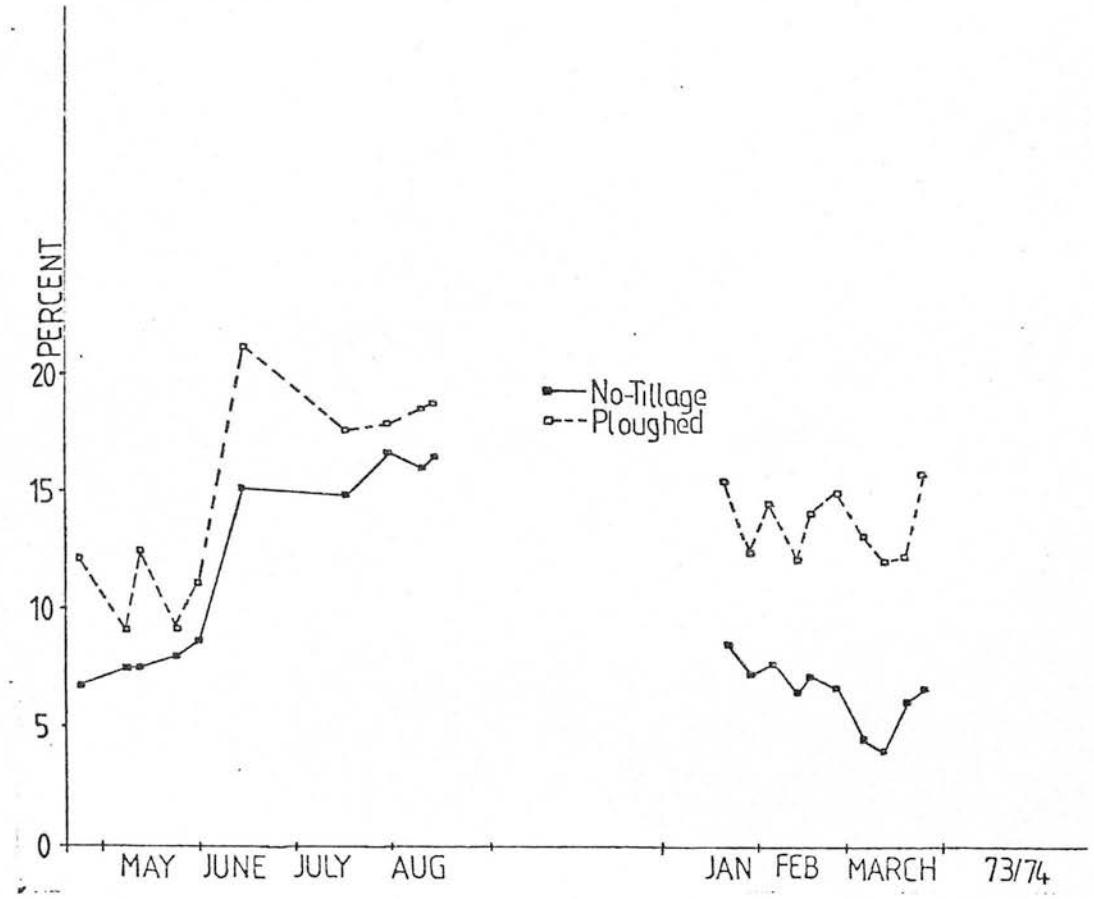
Figures 19 and 20

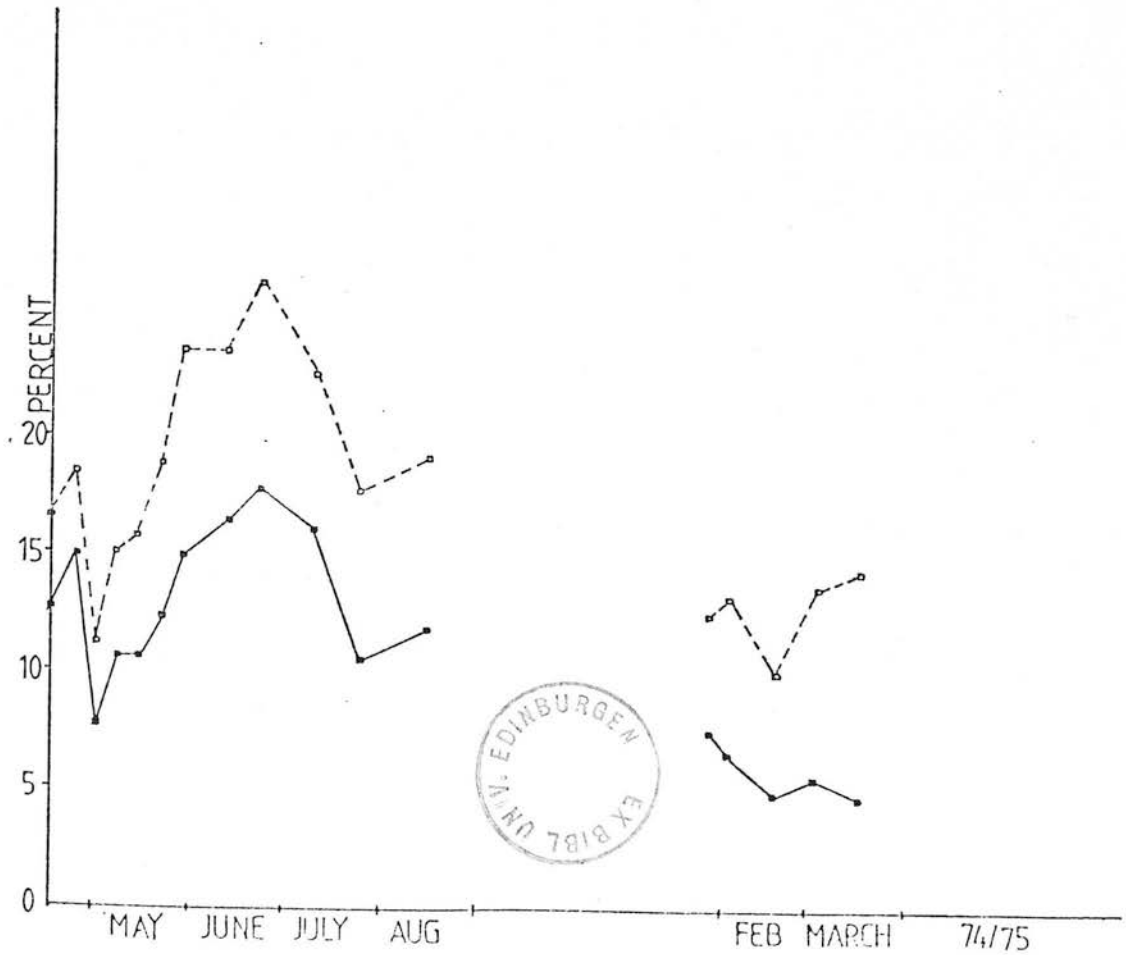
Mean air filled porosity at 15 cm and 30 cm, 1973-4 and 1974-5.



Figures 21 and 22

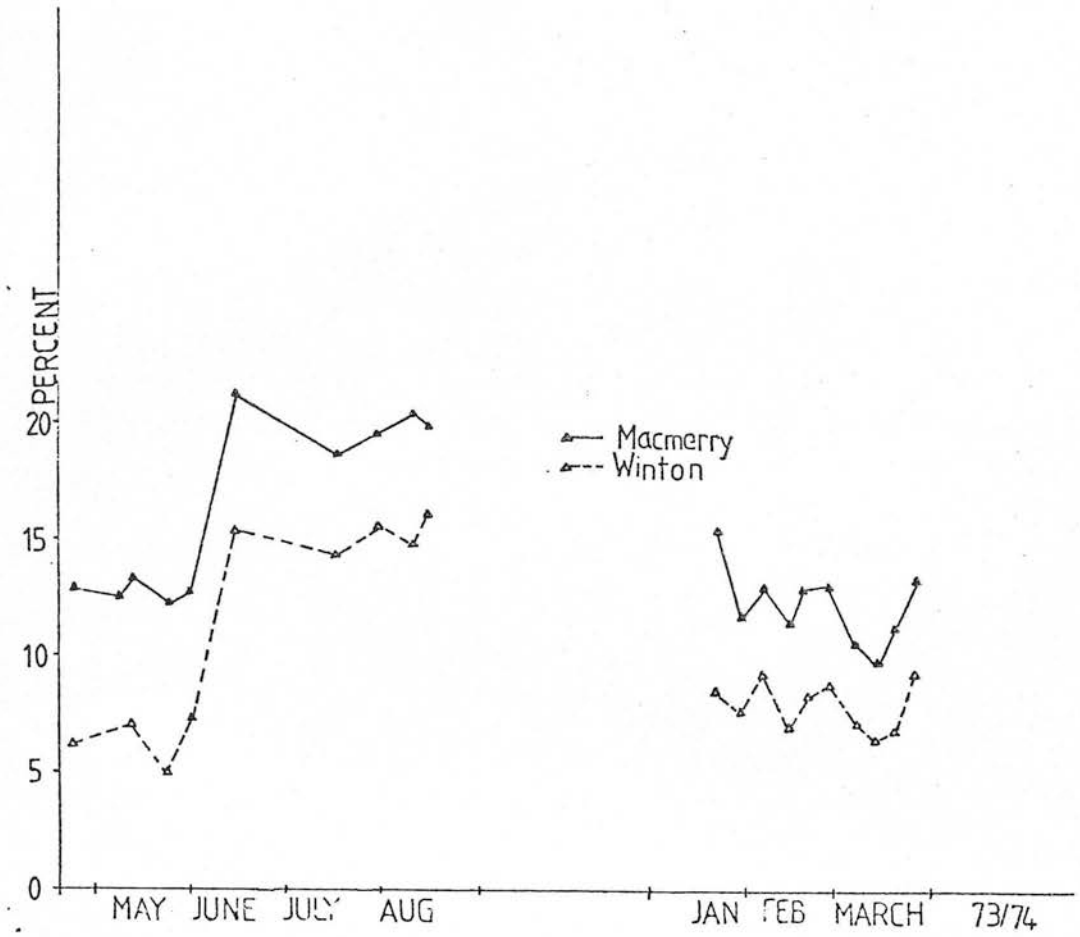
Mean air filled porosity of no-tillage and ploughed plots, 1973-4 and 1974-5.





Figures 23 and 24

Mean air filled porosity of Macmerry and Winton soils, 1973-4 and 1974-5.



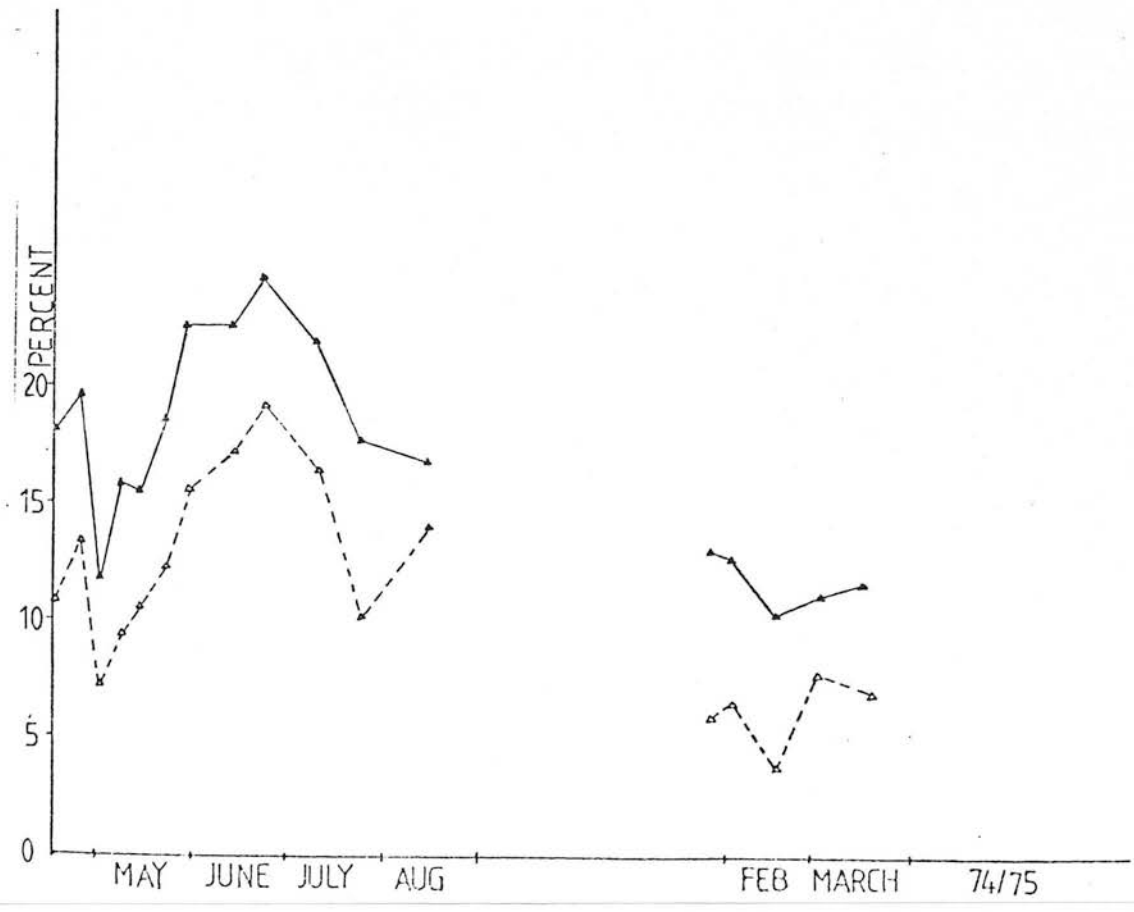


Table 3.

Percentage Organic Matter.

	% O.M.	Standard Error
Overall mean	5.55	
Means for different depths		
0 - 5 cm	6.08	± 0.13
5 - 20 cm	5.86	
20 - 35 cm	4.71	
Means for different cultivation treatments.		
Shallow ploughing	5.35	± 0.16
No-tillage	5.75	
Means for different soil types		
Macmerry soil	6.10	
Winton soil	5.00	

Table of means for the organic matter percentage of the different cultivation treatments at each depth

	No-tillage	Ploughed
0 - 5 cm	6.23	5.94
5 - 20 cm	5.84	5.89
20 - 35 cm	5.20	4.22

Vertical comparison ± 0.19

Horizontal comparison ± 0.27

An analysis of variance of organic matter percentage showed a significant difference with depth of sampling. The organic matter content decreased with depth. There was no significant difference between the organic matter of the cultivation treatments. However, a significant difference was found, at the 5% level, for the interaction between cultivation treatment and depth of sampling. The no-tillage plots had a higher organic matter on the surface and at the lowest depth of sampling, below the depth of ploughing, the organic matter percentage on the ploughed plots was considerably lower than that on the no-tillage plots.

The lighter Macmerry soil had a higher organic matter than the Winton soil but it is not possible to give a standard error because there is no randomization of the soil types.

Soil Atmosphere: Effect of Treatments

The compositions of the soil atmosphere at the two depths of sampling are compared in figures 25 to 30 and Table 4 in which dates when significant differences were found are identified. Similarly, for the same gases, the data from the no-tillage and ploughed plots are compared in figures 31 to 36 and Table 5. Figures 37 to 42 compare the two soil types.

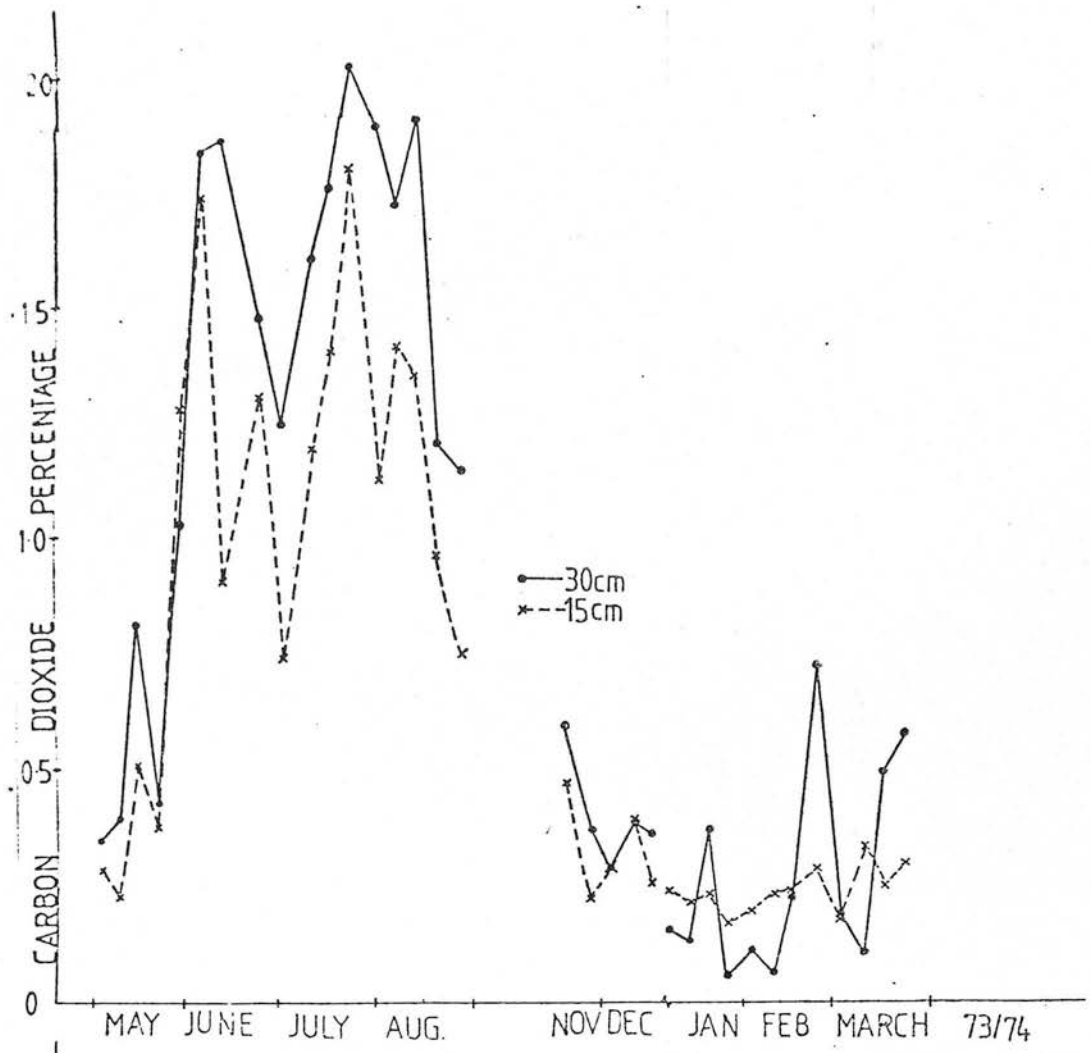
Overall treatment means of the composition of the soil atmosphere were also calculated for each of the four main sampling periods (two growing seasons and two winters). This data was analysed to examine overall trends of the effect of treatments on the composition of the soil atmosphere.

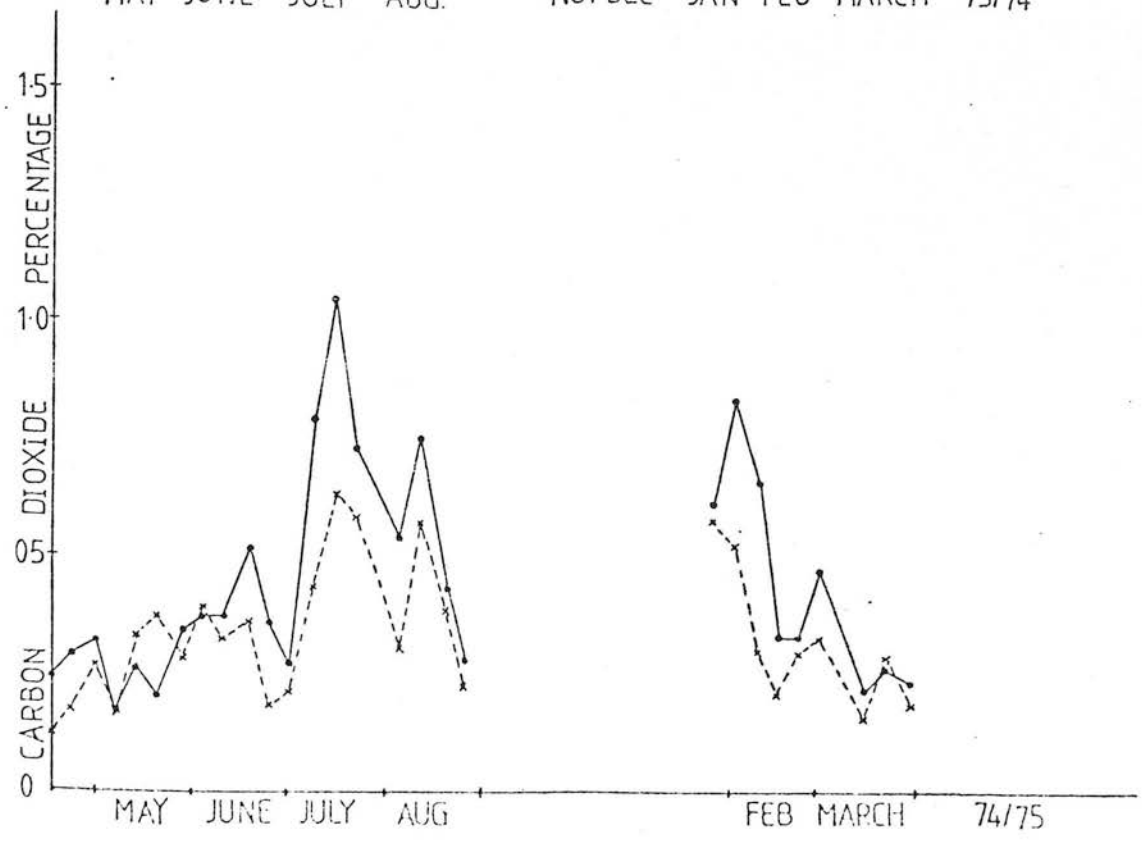
Soil atmosphere at 15 cm and 30 cm.

In the first growing season, 1973, the carbon dioxide percentage in the soil atmosphere at 30 cm was consistently higher than at 15 cm. There was only one occasion when the 15 cm carbon dioxide percentage was higher and this was non-significant. For the other sampling dates on only five occasions was it found that the carbon dioxide percentage was not significantly higher at 30 cm than at 15 cm.

Figures 25 and 26

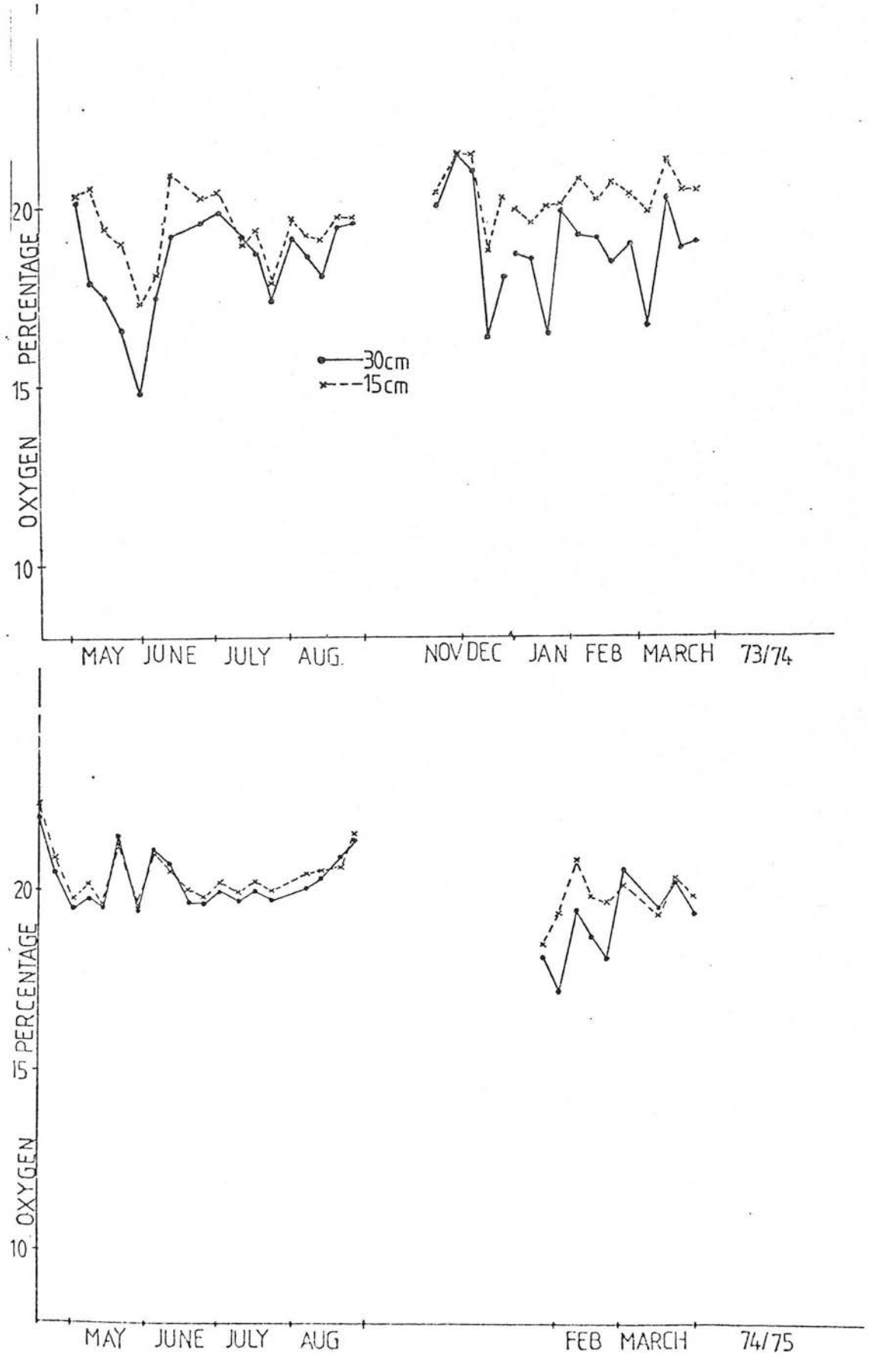
Mean carbon dioxide percentage in the soil atmosphere from probes at 15 cm and 30 cm, 1973-4 and 1974-5.





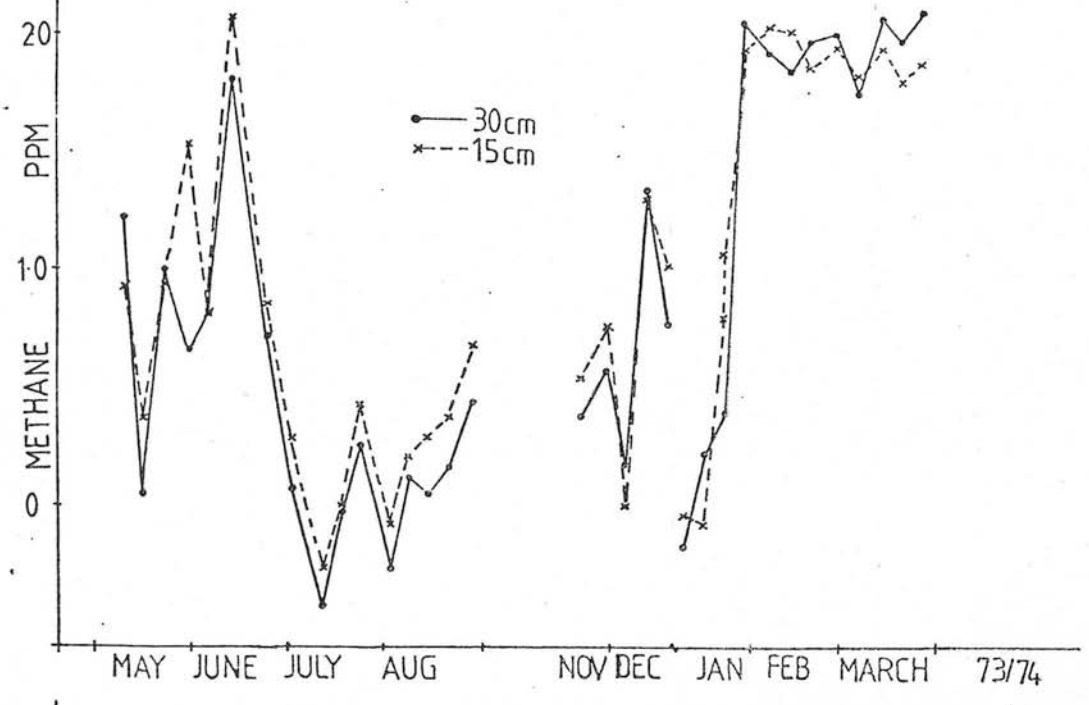
Figures 27 and 28

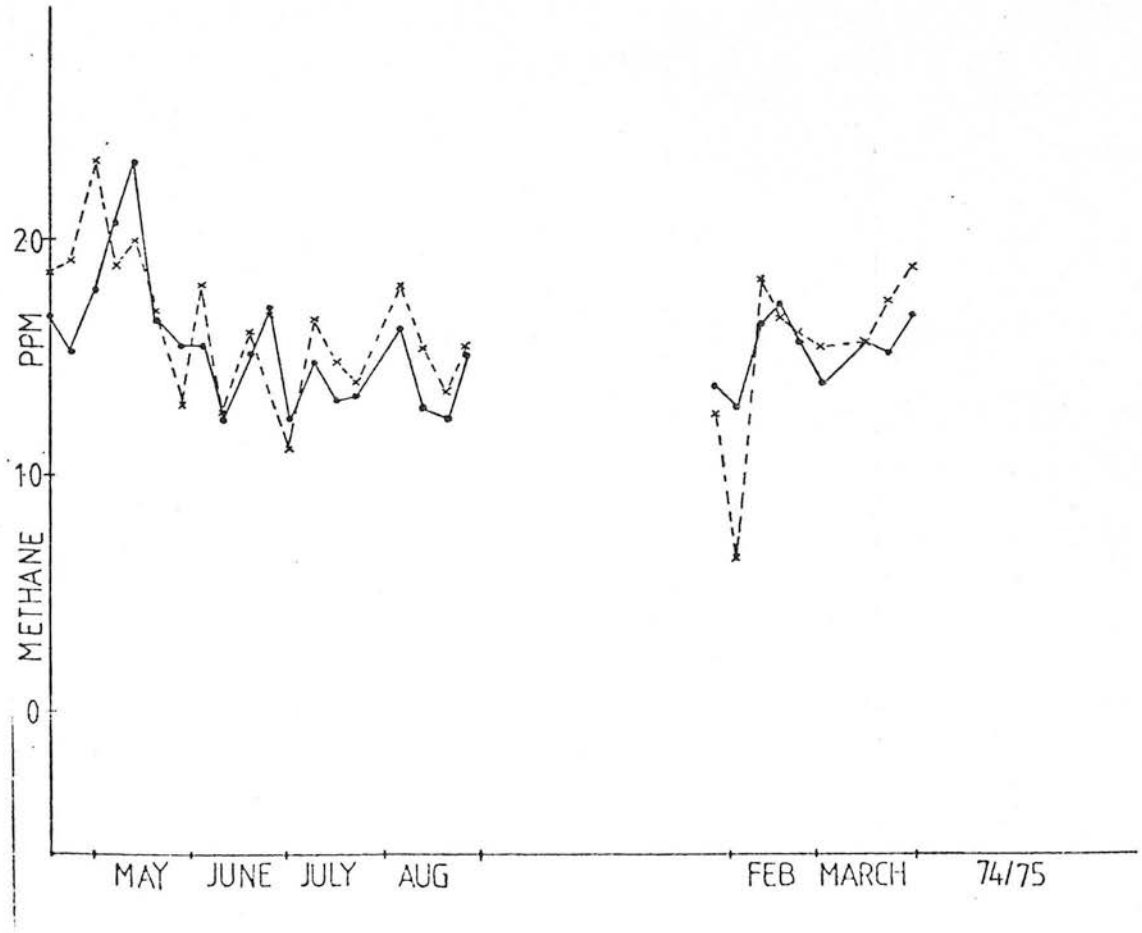
Mean oxygen percentage at 15 cm and 30 cm depths of sampling, 1973-4 and 1974-5.



Figures 29 and 30

Means for methane ppm at 15 cm and 30 cm depths of sampling, 1973-4 and 1974-5.





Refer to Table 4 for those dates in Figures 25 to 30 for which significant differences were identified.

Table 4.

Occasions on which significant differences were found between the means for the two depths, 15 and 30 cm.

Sampling date	Gases			Sampling date	Gases		
Growing Season '73	CO_2	O_2	CH_4	Winter 73/74	CO_2	O_2	CH_4
4th May			-	22nd November			
10th ..	*	**	*	29th ..			
16th ..	*	**		5th December			*
23rd ..		*		13th ..			
30th ..		**	*	19th ..		*	*
6th June				10th January			
13th ..	**		*	17th ..			**
25th ..		**	*	23rd ..		**	
2nd July	***	*	*	30th ..			
12th ..	***			6th February			
18th ..	*			14th ..	**		
24th ..			**	19th ..		*	
2nd August	***			27th ..			
8th ..	*		**	7th March		*	
14th ..	**		**	14th ..	**		
21st ..	**		**	20th ..			
28th ..	***			27th ..			**
Growing Season '74				Winter 74/75			
18th April				28th January			
25th ..	*		*	4th February	*	*	**
2nd May				11th ..	*	*	
9th ..				18th ..		*	
15th ..				25th ..			
22nd ..	*			4th March			*
29th ..				18th ..			
5th June				25th ..			
12th ..				1st April			
20th ..							
26th ..	*						
3rd July							
10th ..	**						
17th ..							
24th ..							
7th August	*		*				
14th ..	**		*				
21st ..							
27th ..							

* Difference between means significant at P 0.05
** Difference between means significant at P 0.01
*** Difference between means significant at P 0.001

The data is shown on graphs 25 to 30.

The situation in the following winter was not so clear. The level of carbon dioxide was considerably lower and any differences in the soil atmosphere at the two depths was generally not significant. On the two sampling dates when a difference was identified the carbon dioxide percentage in the soil atmosphere from the 30 cm probes was lower.

In the second growing season and winter, 1974/75, a trend for the carbon dioxide percentage to be higher in the soil atmosphere from the 30 cm probes was apparent again. However, on few sampling dates was this difference significant. (Figures 25 and 26 and Table 4).

Considering the overall means for carbon dioxide there is a clearly significant difference between the two depths in both growing seasons. In the winter sampling periods differences were non-significant.

The oxygen percentage in the soil atmosphere from the same probes, those at 15 cm and 30 cm, again for the first year's data shows a clearer trend than in the second year. In this year, 1973/74, for the first half of the growing season the oxygen percentage at 30 cm was consistently significantly lower. This trend appeared to continue throughout the year. (Figures 27 and 28 and Table 4).

Analysis of overall means of oxygen percentage showed that the oxygen percentage was significantly lower at the 30 cm depth of sampling in all four sampling periods.

Considering the methane component of the soil atmosphere at the two depths of sampling, again only in the first growing season was there any consistent significant differences. Over this sampling period a lower level of methane was found at 30 cm and only in this sampling period were the overall means for depth of sampling significantly different. For the remainder of the sampling periods no differences were found. (Figures 29 and 30 and Table 4).

Soil atmosphere under no-tillage and ploughing

The carbon dioxide level in the no-tillage plots was generally higher than in the ploughed plots. (Figures 31 and 32 and Table 5). On few occasions, with the exception of the winter of 1973/74, was this trend non-significant. In that sampling period, although the results show the same trend, analysis showed this difference to be significant on only one sampling date.

However, analyses of the overall means for the four sampling periods showed that the carbon dioxide percentage of the soil atmosphere in no-tillage plots was significantly higher than the carbon dioxide percentage of ploughed plots in each sampling period.

The oxygen percentage of the soil atmosphere in the first year's sampling seemed to be consistently lower in the no-tillage plots but on less than 25% of the sampling dates was this difference significant. No differences were apparent in the second year's data (Figures 33 and 34 and Table 5).

It was only in the first growing season that the overall mean oxygen percentage in the no-tillage plots was significantly lower than that found in the ploughed plots.

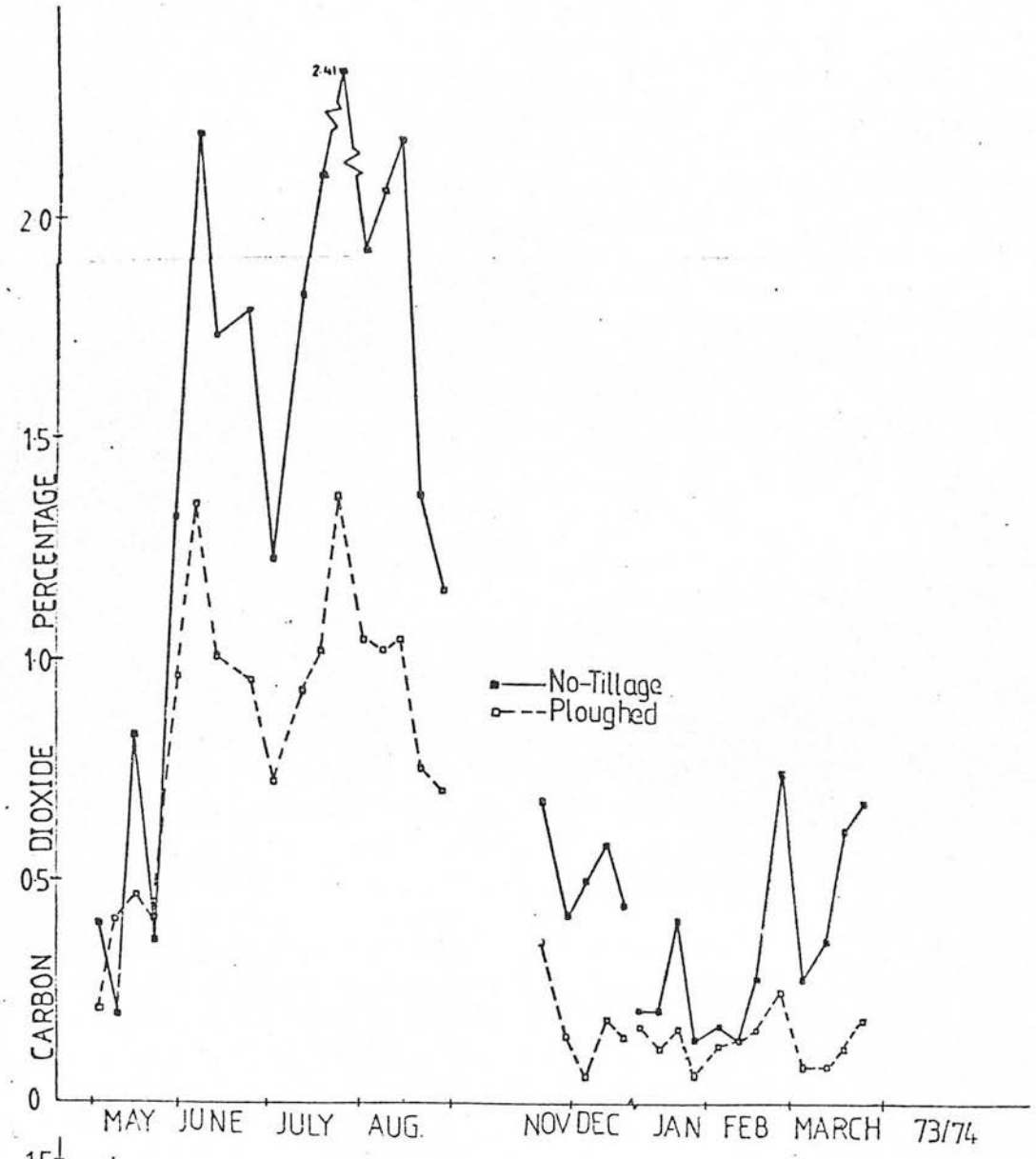
Considering the methane component of the soil atmosphere in the no-tillage and ploughed plots little difference can be identified (Figures 35 and 36 and Table 5). Although in the final winter sampling period, when the overall means were examined, then the soil atmosphere in the ploughed plots was significantly higher in methane than the soil atmosphere in the no-tillage plots.

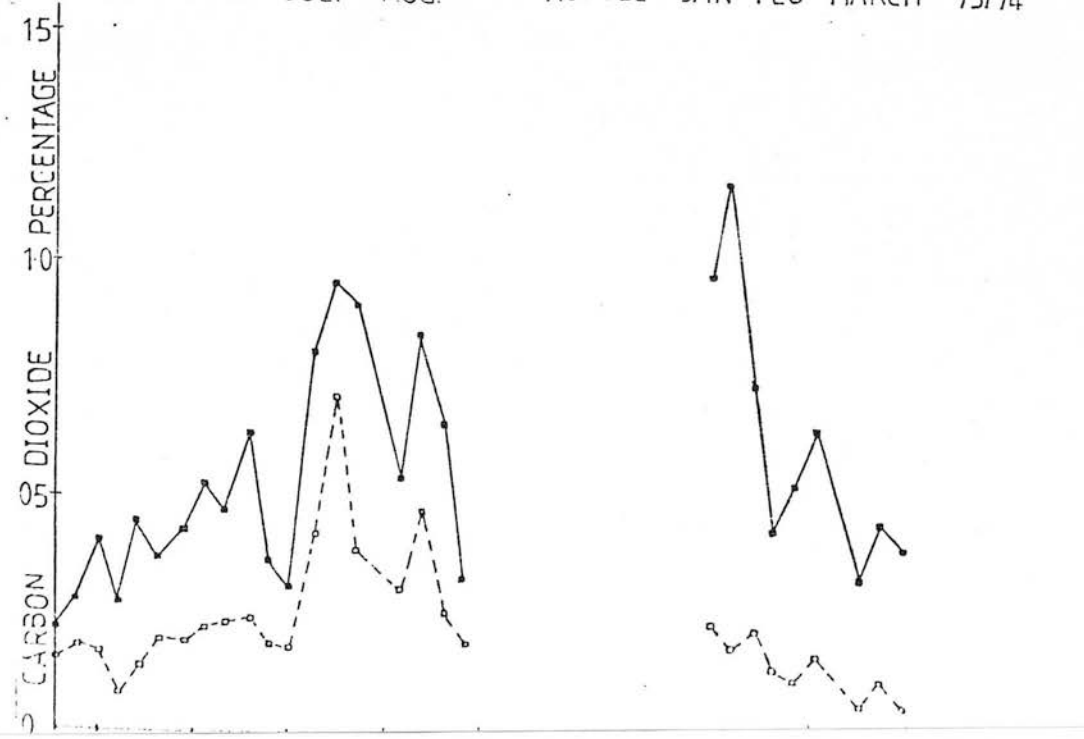
Soil atmosphere in Macmerry and Winton soils.

A comparison between the soil atmosphere from all the sampling probes in the two soil types, Macmerry and Winton, is shown in Figures 37 to 42. No statistical analysis can be carried out on the data from

Figures 31 and 32

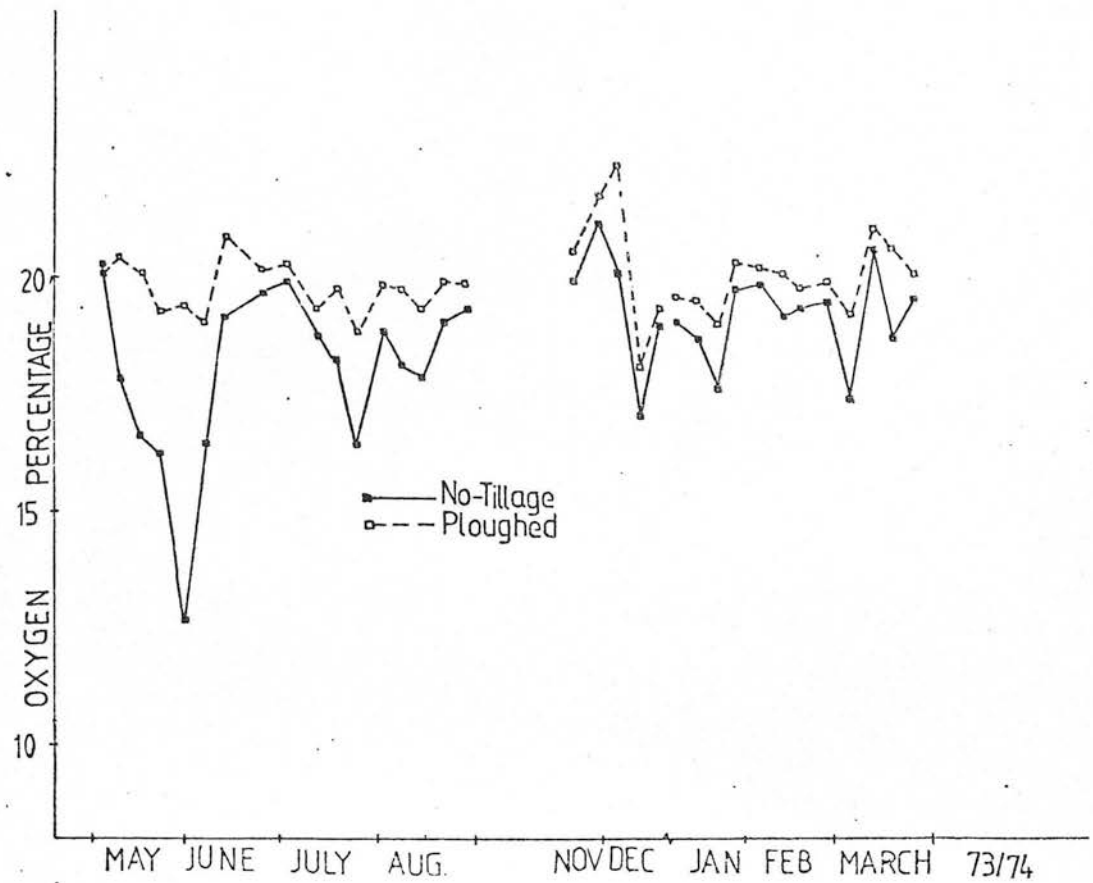
Mean carbon dioxide percentage in the soil atmosphere in no-tillage and ploughed plots, 1973-4 and 1974-5.

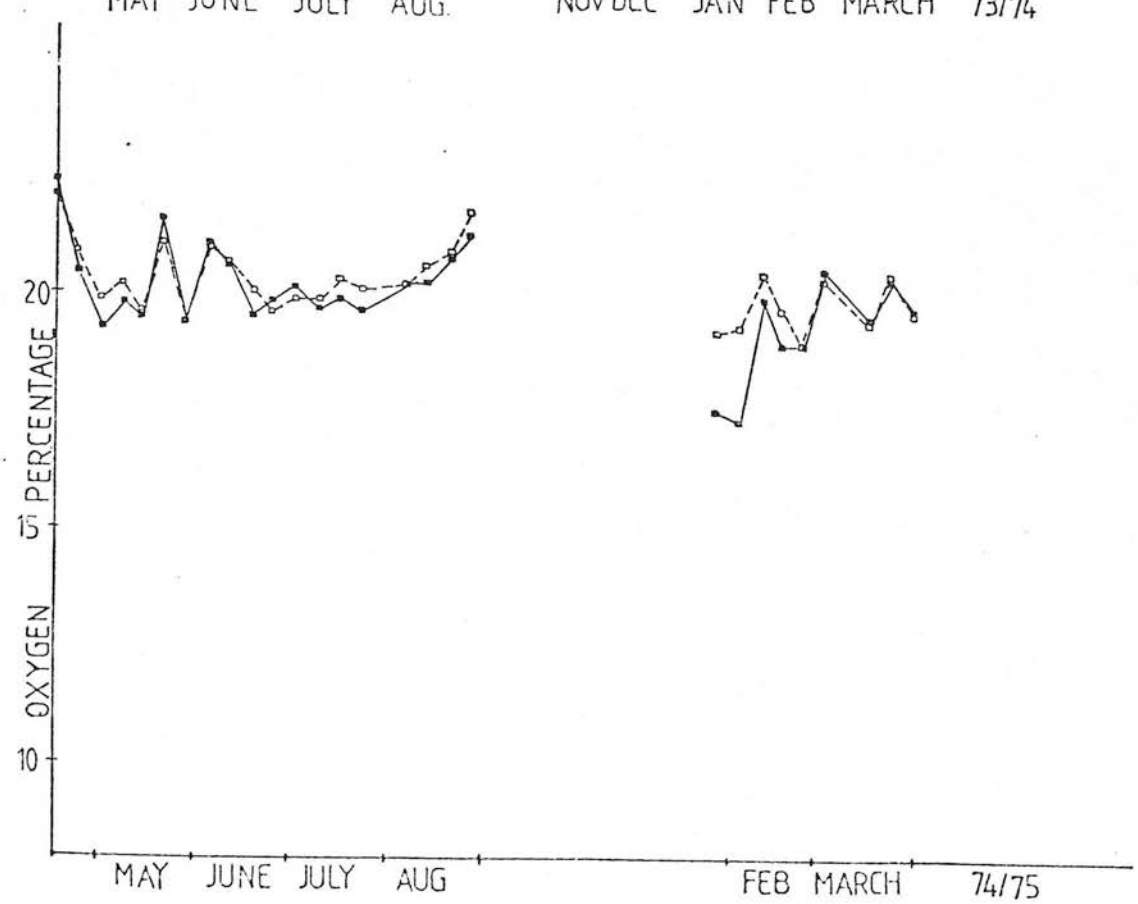




Figures 33 and 34

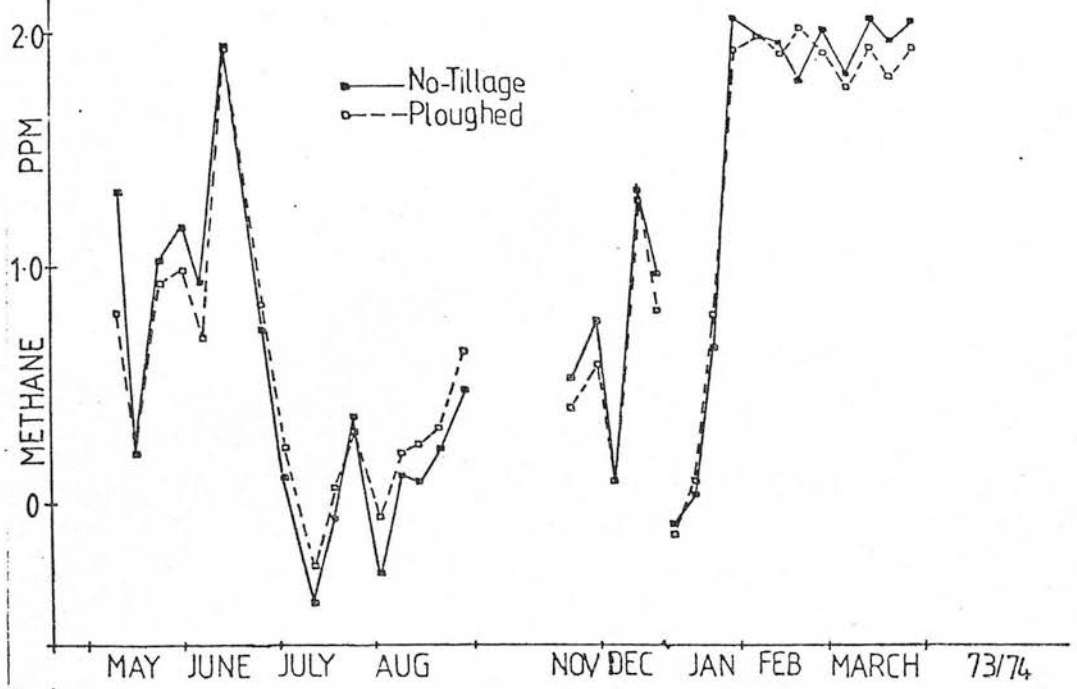
Mean oxygen percentage in the soil atmosphere of no-tillage and ploughed plots, 1973-4 and 1974-5.

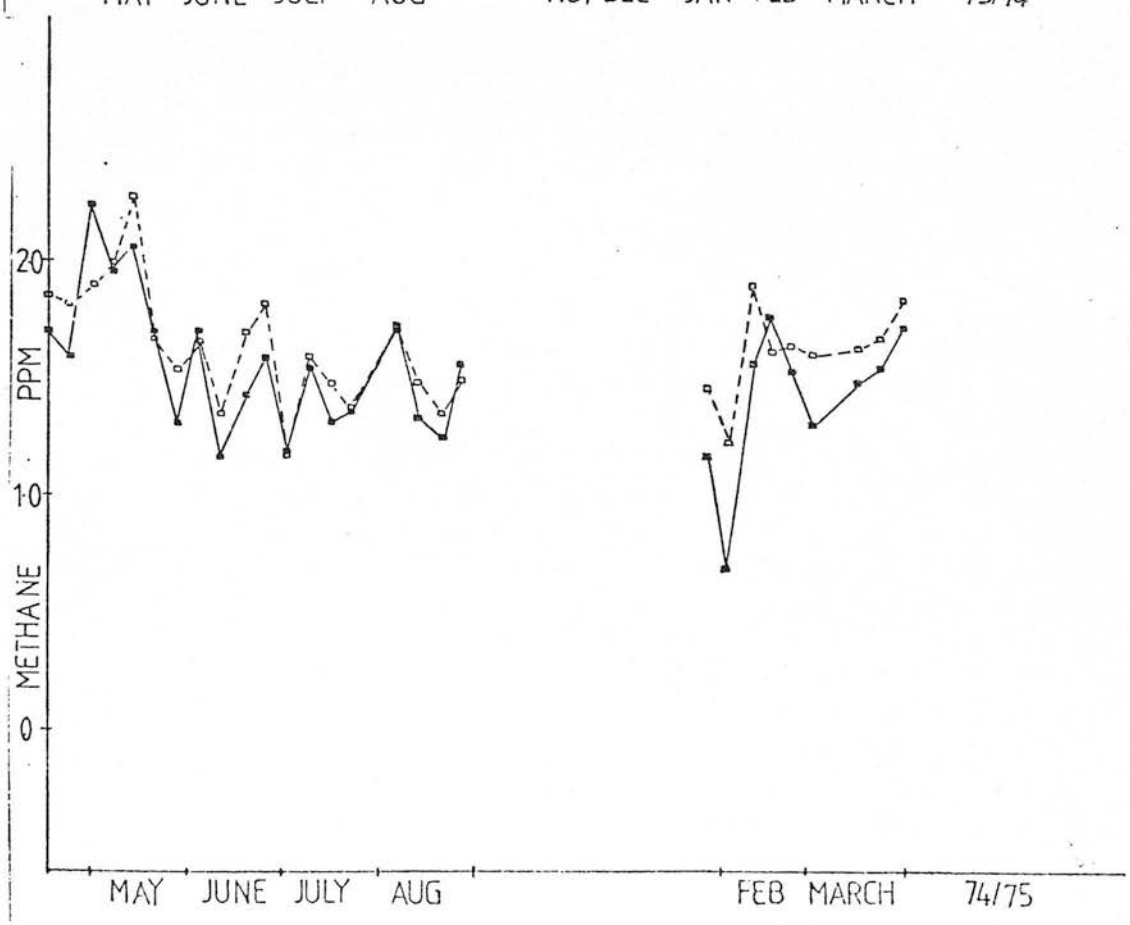




Figures 35 and 36

Means for methane ppm from the soil atmosphere of no-tillage and ploughed plots, 1973-4 and 1974-5.





Refer to Table 5 for those dates in Figures 31 to 36 for which significant differences were identified.

Table 5.

Occasions on which significant differences were found between the means for the cultivation treatments, no-tillage and ploughing.

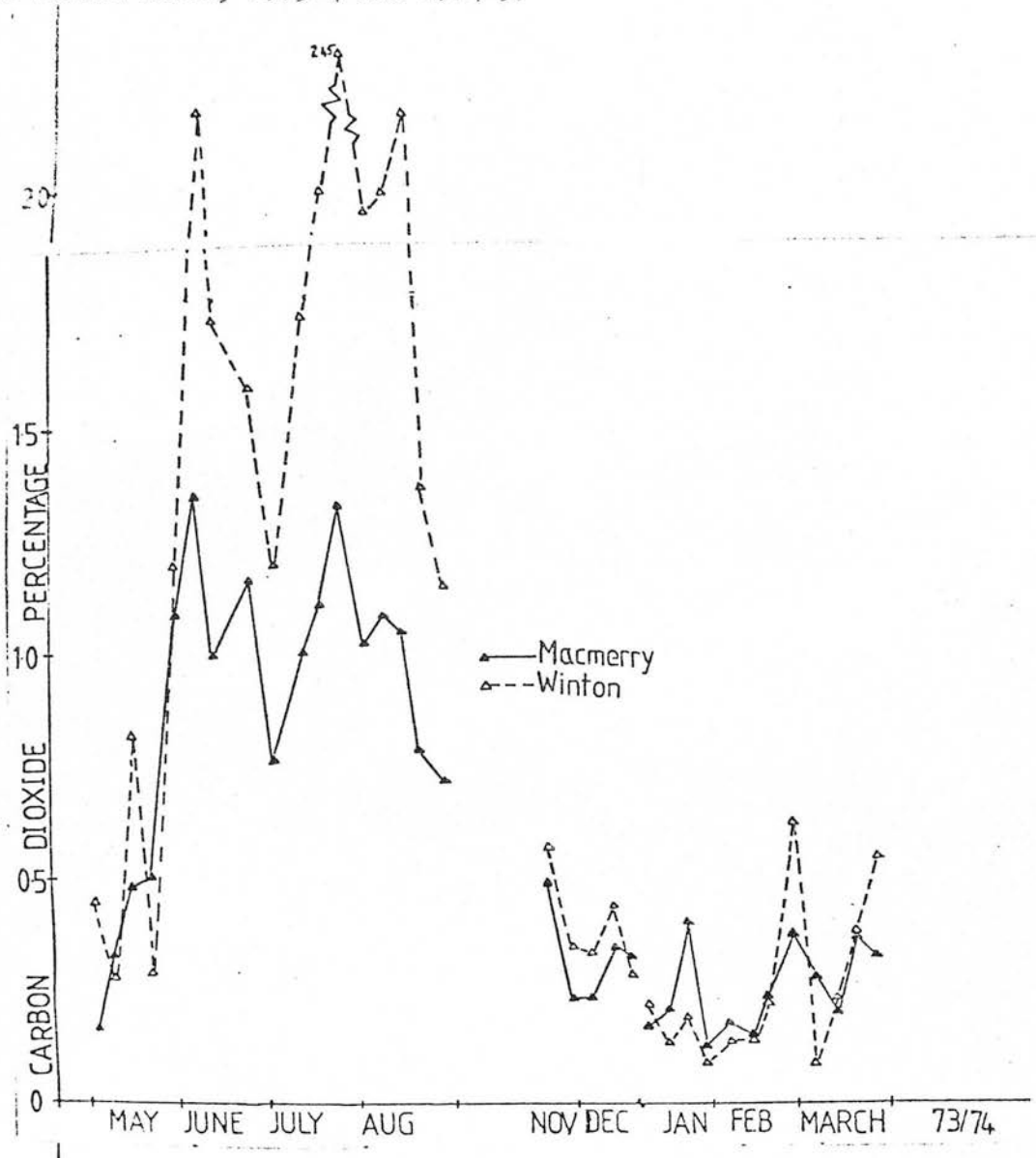
Sampling date	Gases			Sampling date	Gases		
Growing Season '73	CO_2	O_2	CH_4	Winter 73/74	CO_2	O_2	CH_4
4th May	**		-	22nd November			
10th ..	**	**	***	29th ..			
16th ..	*	*		5th December			
23rd ..		**		13th ..	*		
30th ..		**		19th ..			*
6th June				10th January			
13th ..				17th ..			
25th ..	**			23rd ..			
2nd July	*			30th ..			
12th ..	**			6th February			
18th ..	*	*		14th ..			
24th ..		*		19th ..			
2nd August	**		*	27th ..			
8th ..	*			7th March			
14th ..	**			14th ..			
21st ..	*	*		20th ..			
28th ..	*			27th ..			
Growing Season '74				Winter 74/75			
18th April				28th January	**		*
25th ..				4th February	**	*	**
2nd May				11th ..	*		
9th ..	*			18th ..			
15th ..				25th ..	**		
22nd ..				4th March	*		*
29th ..				18th ..			
5th June	**			25th ..	*		
12th ..	*			1st April	*		
20th ..		**	*				
26th ..							
3rd July							
10th ..	*						
17th ..							
24th ..	*						
7th August	***						
14th ..	**						
21st ..	**						
27th ..							

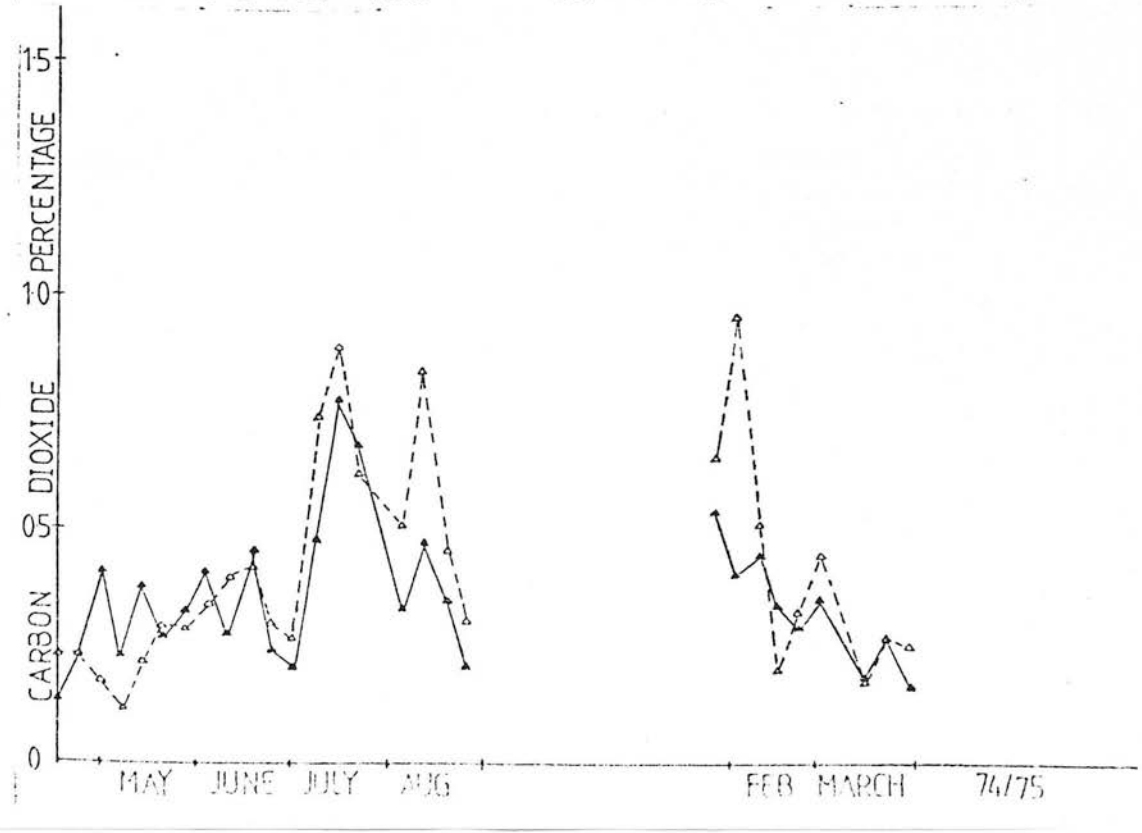
* Difference between means significant at P 0.05
** Difference between means significant at P 0.01
*** Difference between means significant at P 0.001

The data is shown on graphs 31 to 36

Figures 37 and 38

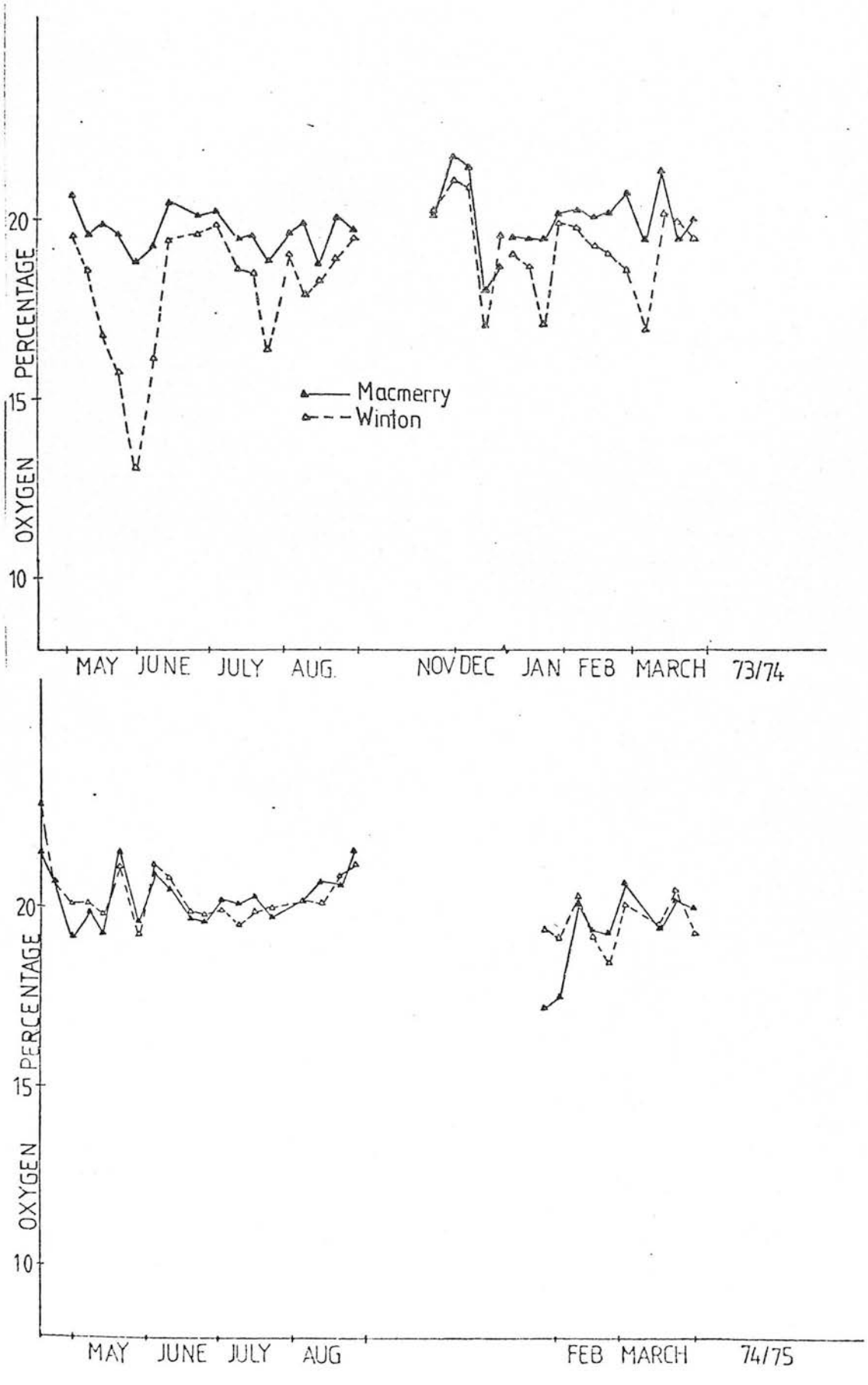
Mean carbon dioxide percentage in the soil atmosphere of Macmerry and Winton soils, 1973-4 and 1974-5.





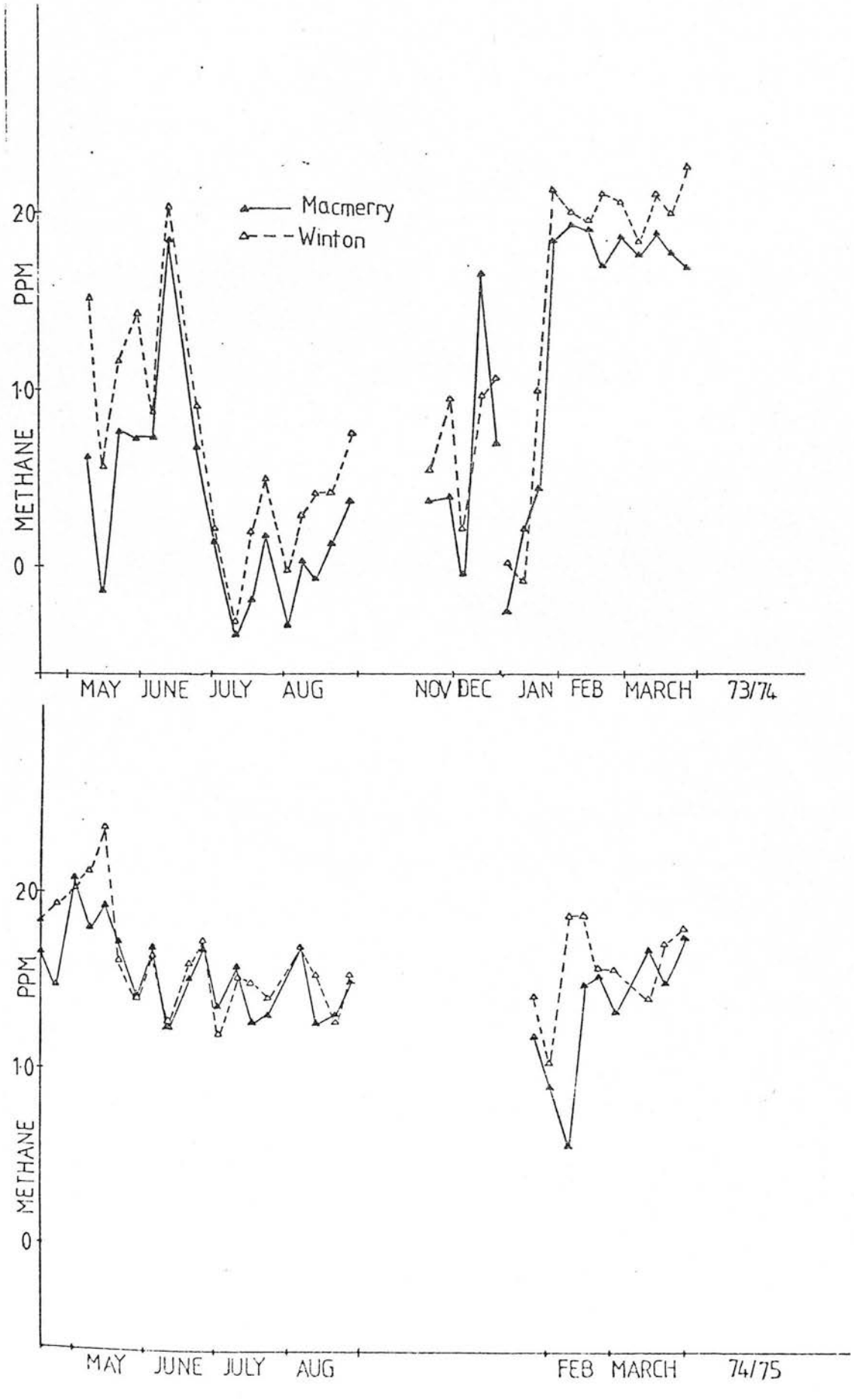
Figures 39 and 40

Mean oxygen percentage in the soil atmosphere of Macmerry and Winton soils, 1973-4 and 1974-5.



Figures 41 and 42

Means for methane ppm in the soil atmosphere of Macmerry and Winton soils, 1973-4 and 1974-5.



the different soils in the field because the soils are, of course, not randomized. Therefore this data is presented to examine any apparent differences but without any supporting statistical analysis.

The carbon dioxide percentage of the soil atmosphere in the two soil types is little different except for during the first growing season. In this period the carbon dioxide percentage of the atmosphere in the Winton soil was consistently higher. (Figures 37 and 38).

Similarly with the oxygen percentage of the soil atmosphere from the two soil types the main differences were apparent in the first growing season. The oxygen percentage of the Winton soil was lower than that of the Macmerry soil in this sampling period. This difference was also apparent during the middle of the first winter. (Figures 39 and 40)

However, the methane component of the soil atmosphere seems to be higher in the Winton soil than in the Macmerry for most sampling dates in the first year and in the final winter sampling period. (Figures 41 and 42)

Ethylene

It is difficult to present results showing the effect of different treatments on ethylene in the soil atmosphere because of the fragmented nature of the detection of ethylene. However considering the total number of probes in which ethylene was found more of these were sited in no-tillage plots than in ploughed plots and also more were at a depth of 30 cm than 15 cm. Roughly equal numbers of probes were in each of the two soil types. On the few sampling occasions when there was enough data to carry out a statistical analysis of the results and significant differences were found between treatment means then a higher mean ethylene ppm was found at 30 cm than at 15 cm and also a higher mean in no-tillage plots than in ploughed plots.

II Flask Analysis

Samples of soil were taken once per month during 1974 and set up

for incubation in flasks as already described. The soil samples represented all treatments. The soil was taken from each of the two cultivation treatments at the different depths of soil atmosphere sampling and from plots with the different soil types.

Samples of the atmosphere in the flasks were withdrawn for analysis at approximately seven day intervals during the period of incubation. Figure 43 shows the mean concentration of ethylene for each month. Soil samples were not taken in August.

A breakdown of the mean results indicates that ethylene was present in the atmosphere of the flasks containing each of the soil samples. Figure 44 gives the ethylene concentration in the soil atmosphere for those soil samples taken in the month of June. Each point on the graph represents the mean of four replicates. For clarity the results for each soil type have been presented separately. An analysis of the results for each separate sampling occasion of the June flasks showed the soil sampled from a depth of 15 cm gave more ethylene than soil from 30 cm. These results were typical for most months of soil sampling. In June also, on two out of the three sampling occasions, in the flasks containing soil from ploughed plots there was more ethylene than in flasks with soil from no-tillage plots. From only one other month's soil, April, was this result repeated. In each other month no differences in the amount of ethylene produced by soil from the different cultivation treatments were found. In three of the months more ethylene was produced in those flasks with Macmerry soil than in those flasks with the Winton soil. For the rest of the months of soil sampling no differences were apparent between soil types.

III Clod Work

The porosity of PTFE tubing to gases was tested first of all. The results are given in Figure 45 where the peak heights from analysis

Figure 43

Mean concentration of ethylene for each month from the soil taken for incubation in flasks.

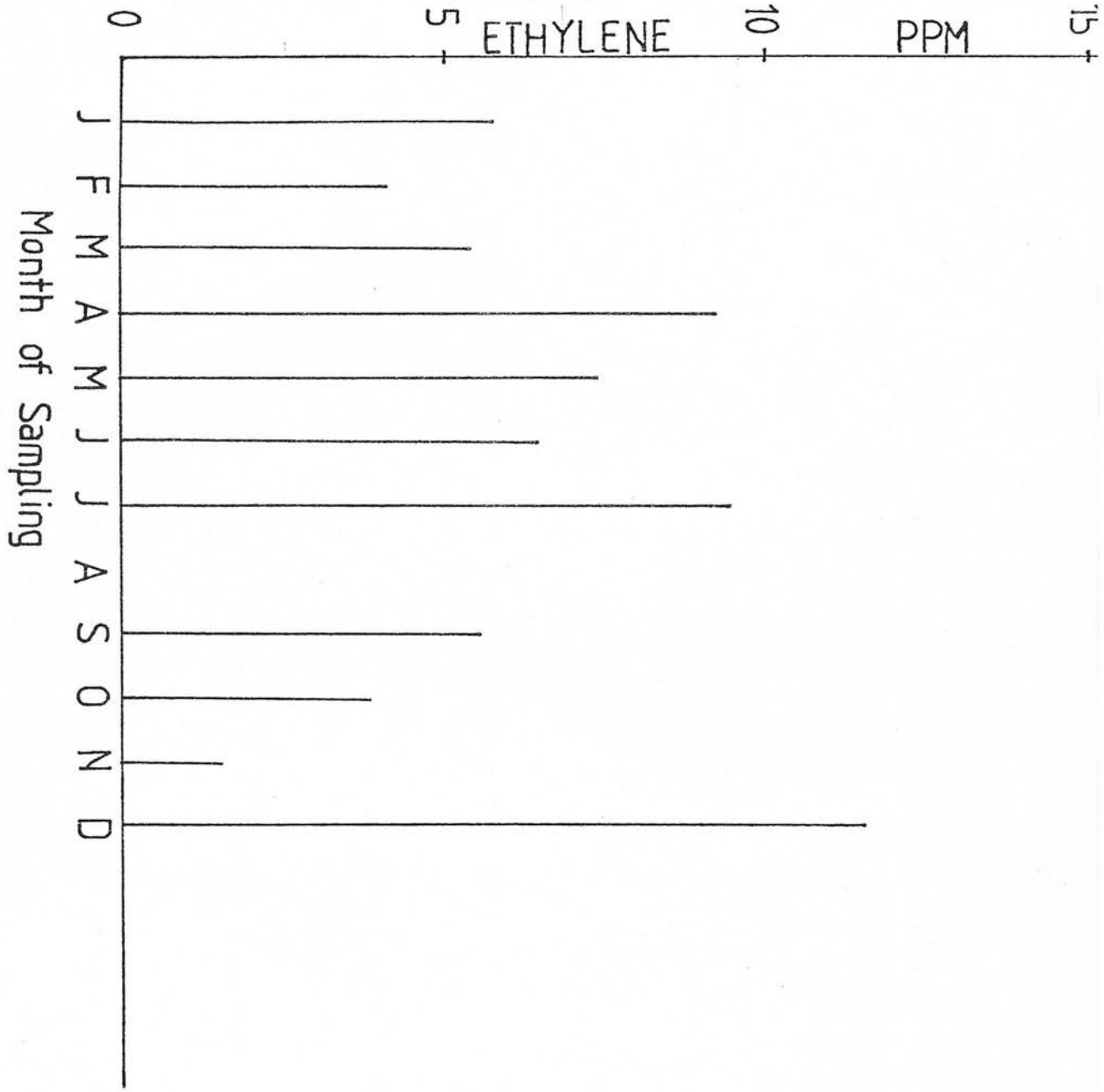
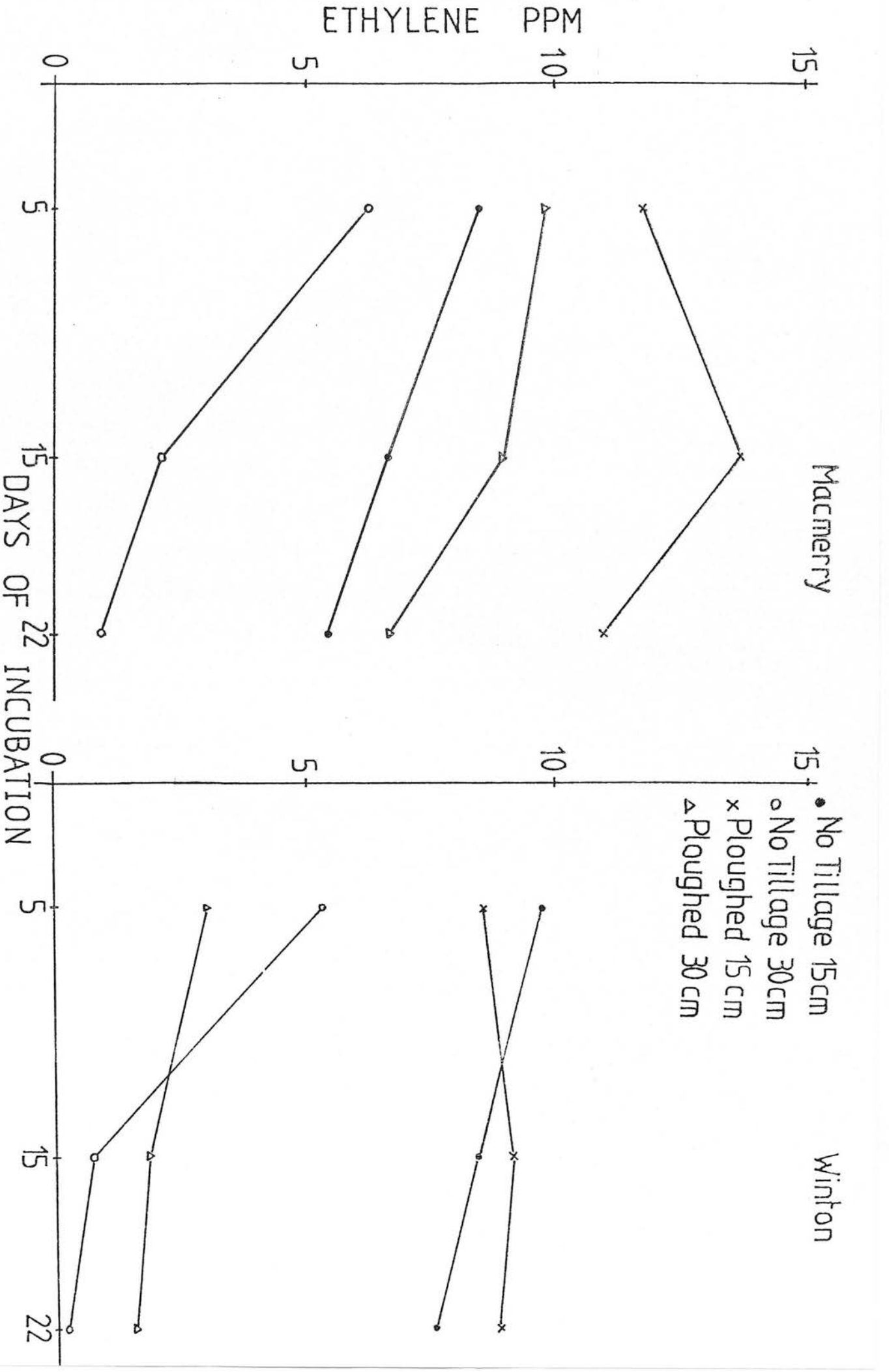


Figure 44

Mean ethylene from incubation of soil samples taken in June.



of the gas withdrawn from lengths of PTFE tubing filled with a gas mixture of known composition are shown. Each set of points on the figure represents a separate test. These show that the tubing is porous to gases. The internal environment of the tubing changed with time and in each case, for carbon dioxide, reached the level of carbon dioxide found in laboratory air within six hours.

In an experiment where the internal atmosphere of laboratory made clods was sampled by means of a single length of tubing two different sizes of formers were used. The clods were sampled at three to four day intervals for a period of two weeks and the samples withdrawn analysed immediately. The results obtained are given in Table 6. This shows that the internal environment of the clods was different to laboratory air. In the internal environment of the clods there was more carbon dioxide than in laboratory air and in both clods ethylene was produced. The amount of ethylene detected increased markedly in the last sample taken.

Table 6

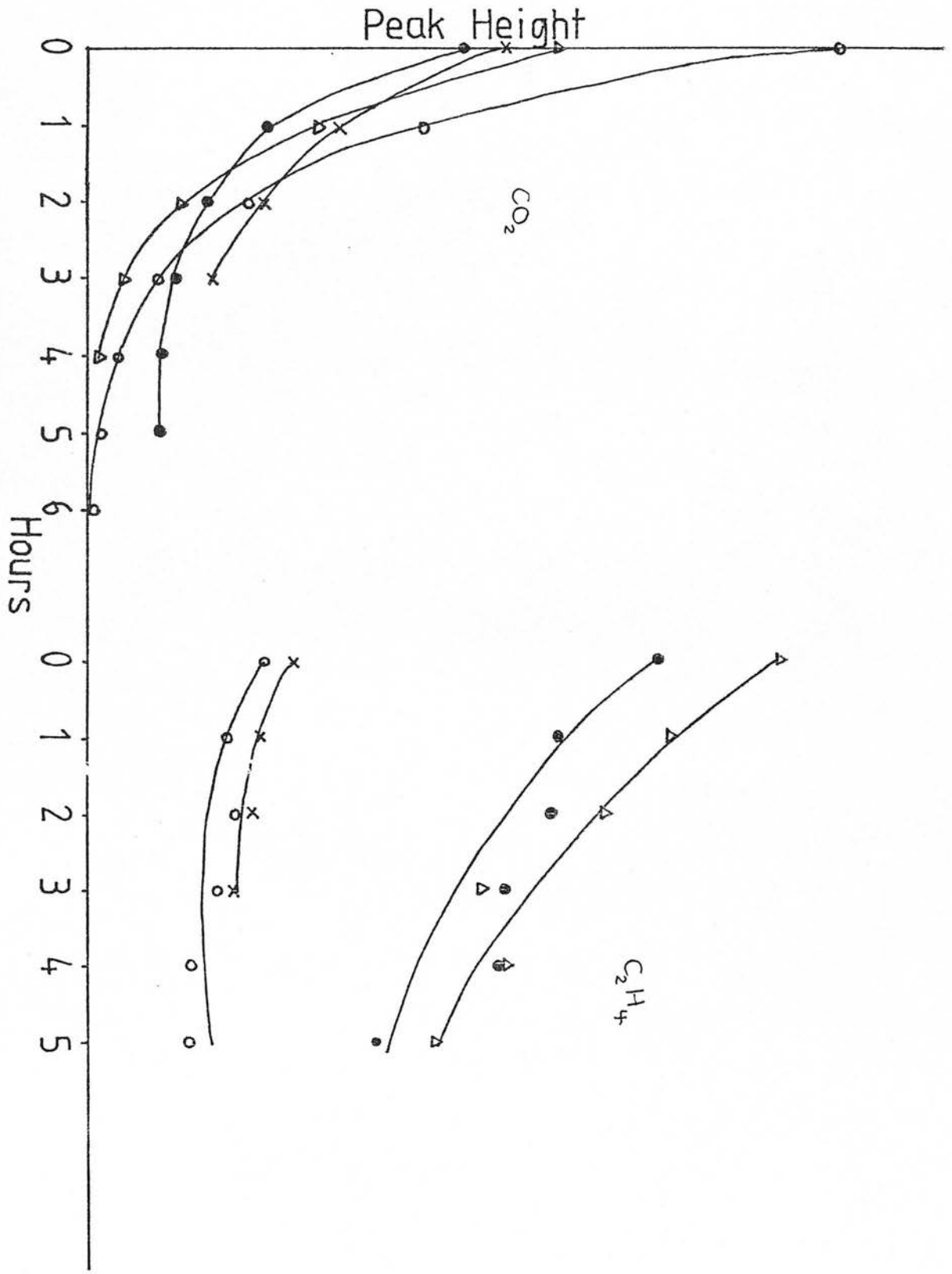
Internal environment of laboratory made clods using one length of PTFE tubing as a sampling tool.

DAY	CLOD A (radius = 8.0 cm)				CLOD B (radius = 11.8 cm)			
	CO_2%	O_2%	CH_4ppm	C_2H_4ppm	CO_2%	O_2%	CH_4ppm	C_2H_4ppm
3	0.53	20.3	1.66	0.06	-	-	-	-
6	0.47	18.3	1.82	0.06	0.58	20.1	1.93	0.03
10	0.47	20.2	1.66	0.02	0.23	17.9	1.31	0.00
14	0.33	-	1.86	0.30	0.56	-	2.04	0.73
Laboratory Air					0.12	20.1	1.44	0.00

When two lengths of PTFE tubing were inserted in the making of a clod a larger former was used with a radius of 17. 6 cm. The results from analysis of atmosphere withdrawn from the two rings of PTFE tubing in this clod are shown in Table 7. On each sampling occasion there was

Figure 45

Change in peak height of carbon dioxide and ethylene from PTFE tubing over a time period.



more carbon dioxide in the atmosphere sampled by the inner tube than that sampled by the outer tube and in both the carbon dioxide was a higher percentage than in laboratory air. Ethylene was detected in the atmosphere sampled by the inner tube but not in that sampled by the outer tube.

Table 7.

Internal environment of laboratory made clod using two concentric rings of PTFE tubing as a sampling tool.

DAY	Inner Tubing				Outer Tubing			
	CO_2%	O_2%	CH_4ppm	C_2H_4ppm	CO_2%	O_2%	CH_4ppm	C_2H_4ppm
3	0.46	15.2	1.75	0.00	0.21	15.4	1.44	0.00
6	0.61	17.4	1.9	0.01	0.39	18.4	2.6	0.00
19	0.35	20.5	1.5	0.08	0.14	18.7	1.5	0.00

The following table gives the dry bulk density of the clods used in the above experiments.

Clod Radius	A 8.0 cm	B 11.8 cm	17.6 cm
Dry Bulk Density	1.29 g/cc	1.31 g/cc	1.25 g/cc

Clods A and B have very similar dry bulk densities. The internal environment sampled from these clods is shown in Table 6. The clod which was constructed with two concentric rings of PTFE tubing (clod radius = 17.6 cm) has a slightly lower dry bulk density than the other two clods. The results obtained using this clod are shown in Table 7.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

Potential of soil for ethylene production

The experiment where soil, from the field under soil atmosphere investigation, was incubated in the laboratory was designed to test whether the soil from each treatment had an inherent capacity to produce ethylene and whether this varied at different times of the year. The soil was incubated under anaerobic conditions because of evidence that in the field a period of anaerobiosis may be necessary to mobilize substrates for ethylene formation (Lynch, 1975).

All soil samples did have the capacity to produce ethylene during each month of the year. This data differs from that of Lynch (1972) who found that soil samples collected in winter produced no ethylene under laboratory anaerobic conditions until methionine and glucose were added. More recently Goodlass and Smith (1978a) incubated a range of soils, some of which had been sampled during the winter, and ethylene was produced by all. One can postulate that in the single soil sampled by Lynch substrates were not available but this was atypical. Goodlass and Smith (1978b) also showed that when soil was amended with barley straw there were large increases in the amount of ethylene produced. This, of course, is the crop being grown in the field where my investigation was made.

An examination of the results of one month, June, (figure 44) did show differences in the amount of ethylene produced by soil from the different treatments but even so ethylene in varying amounts was produced in the soil from each treatment. The differences in the amount of ethylene produced could be attributed to different concentrations of substrates. In June and most other months more ethylene was produced in flasks containing soil from a depth of 15 cm than flasks with soil from 30 cm.

This is in line with the significant decline in soil organic matter with depth. Similarly the differences in the amount of ethylene produced by the two soil types can be linked to differences in organic matter. The lighter soil, which had higher organic matter content, produced more ethylene in those months when differences between the soil types were found.

The conclusion has to be drawn that in the field the substrates were available, or could be made available, for the production of ethylene at all times of year and in each treatment. When ethylene was not detected in the field therefore, there are several possible reasons. Firstly, conditions may not have been suitable for its production. These conditions would include too low a soil temperature or lack of anaerobiosis, whether this is necessary to mobilize substrates or in the actual production of ethylene in the soil. Secondly, it is also possible that some production of ethylene is not detected by the sampling technique used. The probes sampled the macropore structure at the depth of sampling and not necessarily the intra-crumb pores of soil aggregates. Pockets of ethylene may have existed in microhabitats in the soil which may be simulated in the laboratory flask analysis of soil.

Thirdly, aerobic soil micro-organisms are said to exist which utilize ethylene (Cornforth, 1975) therefore this may be occurring in the generally aerobic macropore system sampled. Also ethylene produced in the soil and entering the inter-crumb pore system will diffuse rapidly out of the soil unless there is obstruction to diffusion by water in these pores.

Therefore, although ethylene was not often detected and seems unlikely to be detrimental to yield in this experiment it cannot be discounted as a contributory factor because, given suitable conditions, the soils have the capacity to produce substantial amounts of ethylene.

Internal environment of clods

The making of clods in the laboratory was found to be difficult. Those produced were unwieldy and not representative of the size of clods encountered in the field. The first problem was obtaining suitable soil. The use of a soil shredder was a particularly dusty procedure but soil with a minimum of soil crumbs was achieved as described in chapter three. Another problem that had to be overcome was that of smearing of the sides of the clod. Only by particularly careful removal of the former, in which the clod was made, was this avoided. A third problem was the incorporation of the PTFE tubing. The length of tubing that had to be used so that $1cm^3$ samples could be withdrawn was 195 cm. This had an internal volume of $3cm^3$. This length of tubing was difficult to handle and the most convenient way was to coil the tubing, tie it lightly in the coil, and then incorporate this into the clod as it was being made. Care had to be taken not to compress the tubing. It was found that the tubing collapsed only when it was pressed into already compacted soil.

The use of PTFE tubing as a sampling tube was shown to be successful and therefore it can be concluded that the tubing does have a potential as a sampling tool. Little information, however, has been gained about the internal environment of clods because only a small number of clods were made. An improved technique for constructing clods would have to be developed before this information could be obtained. However, such information as was obtained demonstrated the possibility of poorer aeration and damaging concentrations of ethylene in the centre of clods.

Other possibilities for PTFE tubing would be as a field sampling tool where if the tubing was placed in the field, possibly in a plough furrow, and left undisturbed by subsequent machinery passes, a view of the average soil atmosphere composition could be obtained on a long term basis.

Soil Atmosphere Studies

The growing season of 1973 was wetter than that of 1974. This is borne out by rainfall and soil moisture data. Further, the incidence of water being withdrawn from the sampling probes was very much higher in the first year. The 1973 growing season had a similar amount of rain to the 25 year average but the 1974 season was about 65 per cent of the average. The winter sampling periods were also drier although in 1974-5, prior to the beginning of this soil atmosphere sampling period, more than the average rainfall fell. Monthly rainfall in mm for a 25 year average and for the two years of sampling 1973-4 and 1974-5 are shown in Table 8.

Table 8

Monthly rainfall, 25 year average and rainfall for 1973-4 and 1974-5

	Rainfall in mm.											
	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March
25 year	47.8	56.9	53.1	79.5	86.4	73.2	73.2	77.7	75.2	68.6	52.3	59.9
1973-4	45.1	100.8	25.4	88.9	42.5	24.7	60.0	29.2	65.6	71.1	50.3	62.4
1974-5	23.4	26.8	42.3	73.4	46.0	79.7	55.1	102.3	134.4	127.2	35.3	38.3

The soil temperature was also different in the two growing seasons with a higher soil temperature being recorded in the first year, after the beginning of June. Before this date, however, 1974 soil temperatures were higher.

The composition of the soil atmosphere in the two growing seasons differed, with the wetter season, 1973, having a higher carbon dioxide and a lower oxygen content. However, the incidence of ethylene detection was higher in the 1974 growing season and the overall mean for ethylene reached the highest level recorded in May of that year.

The winter sampling periods of both years were fairly similar. Soil temperatures recorded averaged 3.5°C and soil moisture fluctuated around

27% W/W. The composition of the soil atmosphere in the two winters was also similar.

Very few field studies have been made on the soil atmosphere and therefore there is little data by which to make comparisons.

Carbon dioxide

Carbon dioxide levels reached a maximum in midsummer. This confirms the observations made by Boynton and Compton (1944) who made a long term study of the soil atmosphere sampled at 1, 3 and 5 foot depths.

In the growing season of 1973 the levels of carbon dioxide found were considerably higher than those found in 1974. The likely reasons for this must be discussed. In the first year, after the beginning of June, soil temperatures were higher than in the second year and hence, presumably, microbial activity was greater. During this year also soil moisture was higher giving some obstruction to free diffusion of carbon dioxide out of the soil. However, carbon dioxide is considerably more soluble in water than oxygen and hence the soil moisture is not such an impediment to diffusion of carbon dioxide as it is to diffusion of oxygen. In the second year one must conclude that the lower carbon dioxide levels found were a result of a combination of lower activity in the soil and, because of the low soil moisture, a greater proportion of the carbon dioxide that was formed being able to diffuse out of the soil.

Winter soil temperatures are such that microbial activity will be low and hence a lower level of microbial carbon dioxide production would be expected in the winter. Also, because the crop was spring barley, there was no crop root respiration. On average the carbon dioxide percentage of the soil atmosphere was lower in winter than during the growing seasons.

Oxygen

Oxygen levels in general were very much higher than those found by Smith and Dowdell (1974). They sampled a heavy clay soil and found oxygen

concentration to be below 10 per cent for much of an equivalent winter sampling period. After mid-April the oxygen component of the soil atmosphere at comparable depths to this study gradually rose to about 19 per cent by July. In a more permeable clay soil they found oxygen concentrations at equivalent depths fluctuated around 16 per cent and did not rise above 19 per cent. As can be seen in figures 3 and 4, oxygen concentrations in neither year were as low as these figures. An average figure for the whole of the sampling period was 19.54 per cent oxygen, and the lowest overall mean recorded was 15.94 per cent oxygen at the end of May 1973.

The period of lowest oxygen concentration occurred in the early growing season of 1973. This was a period of rising soil temperature and relatively high soil moisture. One can postulate that during this period, because of the rising soil temperature, microbial activity was high but that there was impedance to diffusion of oxygen because of the soil moisture. The overall mean for free pore space on each sampling date at this time of the year was below 12 per cent. It was, on average, 9.6 per cent. It has been suggested that there is only obstruction to diffusion in the gas phase when the total gas filled pore space is lower than 12 per cent (Currie, 1962; Wesseling and Van Wijk, 1957). Therefore, if this is the case, at this time of the year there was obstruction to diffusion.

During the early growing season of 1974, the equivalent period of rising soil temperature there was less rainfall than in 1973, the soil moisture was lower and air filled porosity above 12 per cent. Also, during the winter, although soil moisture was high and the mean air filled porosity below 12 per cent, the soil temperature was very low generally below $5^{o}C$.

The low level of oxygen found in the soil sampling probes in the early growing season of 1973 is not in itself inhibitory but may be indicative, at that level of air filled porosity, of the presence of

anaerobic zones. It is only when oxygen concentration is almost zero that plant growth will be impeded by lack of oxygen (Greenwood, 1968). Therefore, the soil sampling procedure gives an indication of the oxygen component of the soil atmosphere on a broad basis. It can only indicate the possibility of there being anaerobic regions somewhere within the soil structure. It must be stressed that a period of anaerobiosis of only a short duration, of a few hours, can damage root systems (Letey et al, 1962; Huck, 1970; Kramer, 1951).

Methane

Methane is formed in the soil by microbial metabolism of non-gaseous products of primary fermentation. It is however biologically inert and therefore levels found in the soil atmosphere are only of interest as an indicator of microbial activity. Methane formed in the soil profile will diffuse to regions of lower concentration of the gas. The general tendancy will be for this gas to diffuse out of the soil into the air above. To some extent, therefore, the levels of methane found in the soil will depend not only on the production of methane but on how easily it can diffuse out of the soil. It is a gas that is virtually insoluble in water and therefore soil moisture occupying the free pore space of the soil structure is a considerable barrier to diffusion.

The methane component of the soil atmosphere in each year steadily declined throughout the growing season. This does indicate that as soil moisture declines so the methane produced in the soil is able to more freely diffuse out into the air above.

The methane component of the soil atmosphere in the 1974 growing season was considerably higher than in 1973. This year, 1974, however was the colder and drier of the two years when microbial activity would have expected to have been lower, because of the lower temperature, and also there to be less of an impediment to diffusion of methane out of the soil.

There must be some other factor that was different in the two years. Substrate availability is a factor that will have a considerable bearing on methane production. The yield of barley was greater in 1974 than 1973 (Table 9) and hence one can assume that in the soil that year there was a greater amount of fresh organic matter from a better established root system.

The levels of methane in the winter of the two years were fairly similar suggesting a similar level of microbial activity influenced by the low soil temperature and in both years, because of high soil moisture, an obstruction to diffusion of methane out of the soil.

Ethylene

Ethylene was detected in the soil atmosphere at variable concentrations and with the anomoly of negative concentrations calculated on a few occasions from the calibration curve used. The smallest peak height that was measured was 0.1 cm and on each occasion the chromatograph was used it was recalibrated. This gave a limit of detection of ethylene in the soil atmosphere which varied but on average was 0.05 ppm. In theory the area under the curve on the chromatograph is proportional to concentration. Peak height was, however, the measure used in this data. This could be a contributory factor to explain the anomoly of negative concentrations of ethylene calculated on certain sampling dates. Because a peak height was measured it must be regarded as ethylene present but not an absolute level.

Ethylene has been found to have an inhibitory effect on the root growth of barley at concentrations greater than 0.1 ppm (Smith and Robertson, 1971). On only two occasions, at the beginning of May 1974, was this level of ethylene reached in the soil atmosphere expressed as a mean of all thirty-two sampling probes. However, if only those sampling probes in which ethylene was detected are considered then this level of ethylene is encountered more often.

The levels of ethylene found were not as high as those encountered by Dowdell et al. (1972) when the atmosphere from probes placed at a depth of 30 cm was found to have as much as 5.0 ppm ethylene. The highest individual recording of ethylene in this study was 1.05 ppm in early May 1974 from a probe sited in a ploughed plot at a depth of 30 cm on the heavier soil. On the sampling occasion prior to this, 1.02 ppm ethylene was recorded from two probes both at a depth of 15 cm, in no-tillage plots, one on each soil series.

The period during which ethylene was detected most consistently in the soil atmosphere and when the highest levels were recorded was at the beginning of the 1974 growing season. In this period because soil moisture was low there was little obstruction to diffusion of gases and oxygen levels were high. Soil temperatures were higher by, on average, 1.5°C than during the equivalent period of the 1973 growing season.

In the early growing season of 1973 when soil temperature was rising, the air filled porosity was below 12%, therefore there was obstruction to free diffusion in the gas phase, and oxygen levels were low, it was not a period when ethylene was detected consistently.

During the final winter sampling period on all sampling occasions ethylene was detected in the soil atmosphere from more than ten per cent of the sampling probes and during the same months, February and March, of 1974 ethylene was found from on average a quarter of the sampling probes. Oxygen levels in these months were very close to atmospheric levels, as they were for most of the time during each of the sampling periods. Soil moisture levels were particularly high, fluctuating around a figure of 27% moisture and soil temperature was low, on average 3.25°C. Daily variations in soil temperature in winter diminish fairly rapidly with depth therefore the soil temperature recorded at 9.00 a.m. once per week is a reasonably accurate representation of soil temperature.

Smith and Dowdell (1974) found that ethylene concentrations rose logarithmically with soil temperature during the spring. There is no similar evidence in this data. Lower levels of ethylene were found with very little variation throughout the whole sampling period. Although in May 1974 when higher soil temperatures were recorded than in May 1973, more ethylene was detected.

It is difficult to draw any conclusions from this data on the field conditions which bring about ethylene production. It appears, however, that oxygen levels, as sampled, have little influence on ethylene in the soil atmosphere. The soil does have the capacity to produce ethylene because when incubated anaerobically, without the addition of any substrates for increased microbial activity, ethylene was formed.

Soil atmosphere at 15 cm and 30 cm

The differences in the soil atmosphere at 15 cm and 30 cm can be explained by the longer diffusion pathway for the gases at 30 cm than at 15 cm. The soil atmosphere sampled from probes at a depth of 30 cm was higher in carbon dioxide and lower in oxygen than the soil atmosphere at 15 cm. Carbon dioxide formed in the soil diffuses out of the soil into the air and oxygen diffuses in the opposite direction.

When there were any differences in the methane component of the soil atmosphere at the two depths of sampling a lower level of methane was found in the soil atmosphere from probes at 30 cm. The organic matter content of the soil decreases with depth, there being a greater proportion of roots, and therefore fresh organic matter, nearer the soil surface and hence greater methane production in this region.

Soil atmosphere under no-tillage and ploughing

The soil atmosphere under no-tillage differed from that under ploughing in that the carbon dioxide level was higher under no-tillage. The oxygen component was lower in the first growing season only.

Bulk density is higher in no-tillage plots and together with any differences in moisture content when air filled porosity of the two cultivation treatments was calculated the no-tillage plots had a markedly lower air filled pore space. Therefore there was less pore space for the free diffusion of carbon dioxide out of this soil and hence a higher level of carbon dioxide. A similar situation exists for oxygen with the oxygen of the soil atmosphere used by root respiration and microbial activity being replaced by oxygen diffusing into the soil from the air above. In the second year however oxygen levels in both cultivation treatments were at very similar levels to the air above the soil surface.

Soil atmosphere in Macmerry and Winton soils

In the Macmerry and Winton soils it was during the first growing season that differences in the soil atmosphere were apparent with the carbon dioxide percentage being higher and the oxygen percentage lower in the Winton soil than in the Macmerry soil. The air filled porosity of the Winton soil was consistently lower than the Macmerry soil during all the sampling periods. It appears therefore that it was only in the first, wetter, growing season when air filled porosity was lower that this difference in air filled porosity was critical and was reflected in the differences in the soil atmosphere.

Effect of treatments on ethylene in the soil atmosphere

It is difficult to assess the effect of the different treatments on ethylene in the soil atmosphere because of the fragmented nature of the detection of ethylene. However, ethylene was detected more often in those probes at 30 cm than those at 15 cm and also in more probes sited in no-tillage plots than in ploughed plots. It is in these treatments, the lower depth of sampling and no-tillage, that higher levels of ethylene were found when any differences were apparent. In these treatments air filled porosity was lower impeding diffusion of ethylene out of the soil.

The yield of barley (Table 9, Holmes, pers. comm.) in the first year of this study was lower than that obtained in the second year. In this year, 1973, the no-tillage plots gave a lower yield than the ploughed plots in each soil type. The lowest yield was obtained from the no-tillage plots on the Winton soil. It was in this year and in these plots that the lowest level of oxygen and the highest levels of carbon dioxide were recorded. It is in no-tillage plots, that most ethylene was detected. The levels of oxygen found were not themselves inhibitory to root growth but are indicative of the poor aeration status of these plots. Little work has been done studying the effect of carbon dioxide on growth of barley at the sort of levels encountered in this study. Harris and Van Bavel (1957) studied the combined effect of low oxygen and high carbon dioxide and concluded that plant functions were not appreciably reduced until the ratio of CO_2 : O_2 partial pressures was greater than one. This situation was not found in this soil atmosphere. The time during the growing season when oxygen levels were at their lowest, the second half of May, does not coincide with the peak carbon dioxide levels. Further, ethylene was not consistently found at levels that have been shown to be inhibitory to barley root growth although there is still some reservation about the possibility of ethylene in intra-crumb pores of soil aggregates not sampled by the probes.

Table 9

YIELD OF GRAIN IN T/HA AT 15% MC WITH 100 kg/ha N

	Macmerry		Winton		
	Plough 20 cm	No-tillage	Plough 20 cm	No-tillage	SE
1973	4.11	3.76	4.10	2.93	±0.15
1974	5.55	5.51	5.46	4.70	±0.23
Mean 1968-74	4.49	4.22	4.40	3.42	

From the evidence available it cannot be concluded that the poorer yield of the Winton no-tillage plots are a direct effect of the composition of the soil atmosphere. However it is on these plots that low oxygen, high carbon dioxide and low air filled porosity were encountered. These are generally indicative of the poor aeration status of this soil. Also it is in no-tillage plots that most ethylene was detected.

In particularly wet years it is in the heavier soil with the greater compaction of the no-tillage treatment that the air filled porosity will be reduced to a critical level impeding diffusion of oxygen and carbon dioxide. In the nearly average growing season for rainfall, 1973, it was on these plots that most water samples were withdrawn from the sampling probes. Hence in wetter years these plots will be the most prone to waterlogging.

Ethylene was detected most often in no-tillage plots. A difference in ethylene detection between soil types may well develop in a wetter year with the Winton soil, because of its greater bulk density, being the most susceptible. Therefore, the Winton no-tillage plots are those in which damaging concentrations of ethylene may well be found. It would be interesting to sample the soil atmosphere in these plots during a particularly wet growing season and also to monitor root growth closely. Cubes of soil could be extracted at regular intervals and these sectioned, possibly after embedding in wax, to examine the pore structure and to look for the characteristic curling effect of roots induced by ethylene in the laboratory (Cornforth and Stevens, 1973; Crossett and Campbell, 1975). There is no record of the observation of this type of root form in the field.

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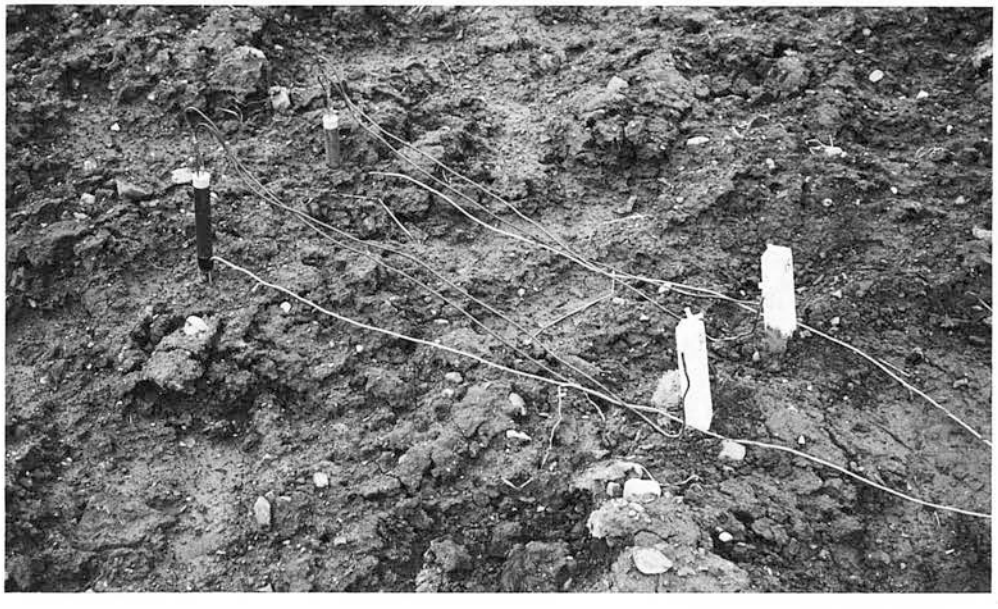
APPENDIX ONE

PHOTOGRAPHS

Photograph 1

Soil atmosphere sampling probes at a depth of 15 cm and 30 cm sited in a no-tillage plot.

Photograph 2

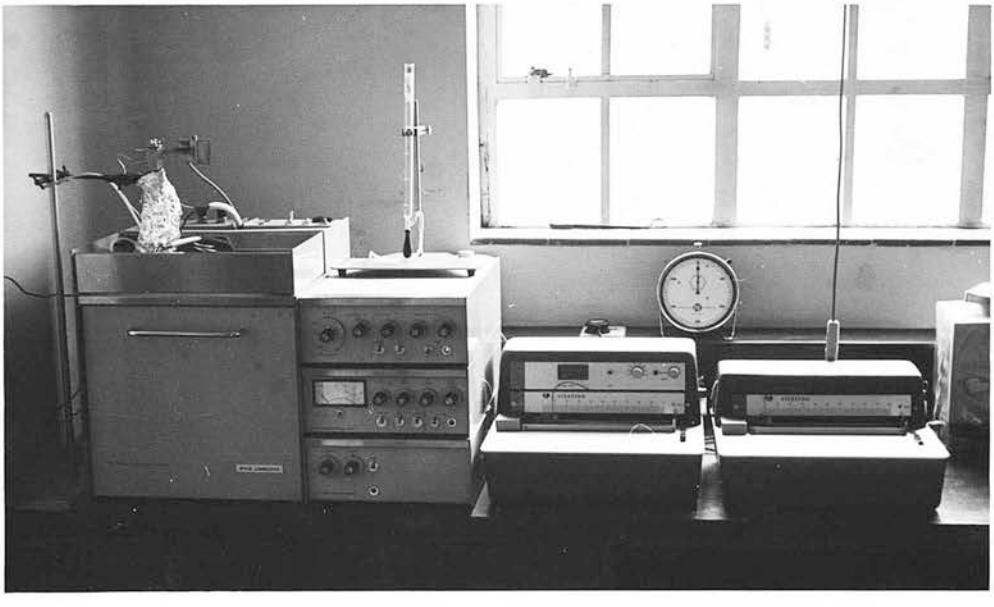


Soil atmosphere sampling probes at a depth of 15 cm and 30 cm sited in a ploughed plot. These probes have thermistors attached.

Photograph 3

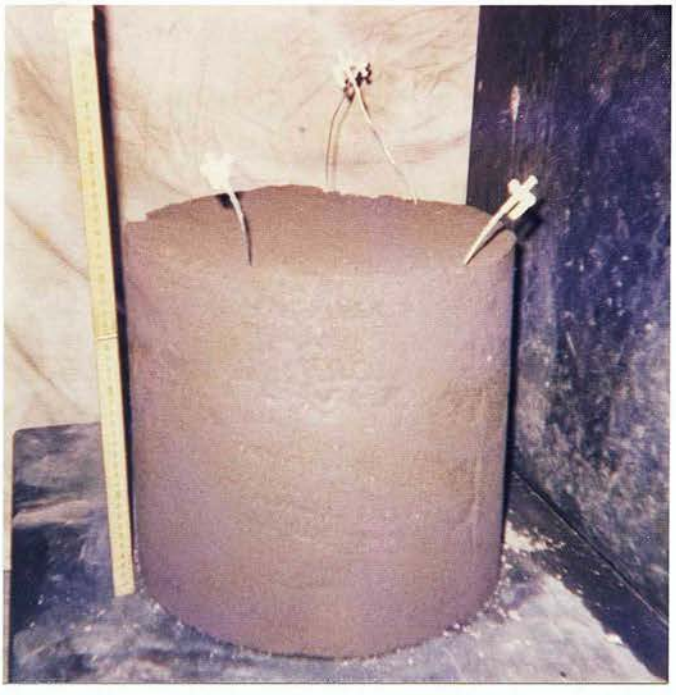
Sampling from a probe: The tap of a syringe was fitted into the tap of a sampling point and the two held together.

Photograph 4



Pye Unicam model 34 chromatograph fitted with a dual detector arrangement of a katharometer and a flame ionization detector each with a pen recorder.

Photograph 5



A laboratory made clod constructed with two concentric rings of PTFE tubing as soil atmosphere sampling tools.

APPENDIX 2

PUBLISHED PAPER

The composition of the soil atmosphere in a barley mono-cropping situation with and without tillage

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ABSTRACT

Weekly gas samples from two depths in a long term experiment were analysed in 1973 and 1974 for carbon dioxide, oxygen, nitrogen, methane and ethylene. An attempt will be made to relate the varying concentrations to soil series, soil moisture, rainfall and temperature. Ethylene has been detected on several occasions.

Proceedings abstract. Annals of Applied Biology,
81, 106 (1975).

APPENDIX 3

Comparative Data of the Soil Atmosphere in the Soil Types, Macmerry and Winton.

Although in the site under investigation the two soil types are, of course, not randomized the data obtained from sampling the soil atmosphere from the different soil types has been statistically compared in the following table. When considering this data it has to be borne in mind that the differences in soil atmosphere from the soil types may not be due to differences in soil type but to differences in the siting of the probes. It is this latter difference that is not minimized because of the non randomization.

Table to show the occasions on which significant differences were found between the means for the soil types, Macmerry and Winton.

Sampling Date	Gases			Sampling Date	Gases		
Growing Season '73	CO_2	O_2	CH_4	Winter 73/74	CO_2	O_2	CH_4
4th May	**	**	-	22nd November			*
10th ..			*	29th ..			*
16th ..		*		5th December			
23rd ..		*		13th ..			*
30th ..		*		19th ..			*
6th June	*			10th January			*
13th ..	*			17th ..			
25th ..				23rd ..			
2nd July				30th ..			
12th July	*	*		6th February			
18th ..	**	*	*	14th ..			
24th ..	*			19th ..			
2nd August	*			27th ..			
8th ..	*			7th March			
14th ..	*	*	*	14th ..			
21st ..	*		*	20th ..			
28th ..				27th ..			*
Growing Season '74				Winter 74/75			
18th April				28th January		*	
25th ..				4th February	**		
2nd May				11th ..			
9th ..				18th ..			
15th ..				25th ..			
22nd ..		*		4th March			
29th ..				18th ..			**
5th June				25th ..			
12th ..				1st April			
20th ..							
26th ..		*					
3rd July							
10th ..		*					
17th ..			*				
24th ..							
7th August							
14th ..	**	*	*				
21st ..							
27th ..							

* Difference between means significant at P 0.05
** Difference between means significant at P 0.01
*** Difference between means significant at P 0.001

This data is shown on graphs 37 to 42.