Céline BOURGEOIS
Ecole Supérieure d'Agriculture
BP 748
49007 ANGERS Cédex 01
FRANCE

Dr David FOWLER
Institute of Terrestrial Ecology
Bush Estate, Penicuik
MIDLOTHIAN
EH26 OQB
SCOTLAND

THE EMISSION OF METHANE FROM PEAT WETLANDS

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Chapter 1: INTRODUCTION

1)METHANE - A GREENHOUSE GAS

1.1-CLIMATE CHANGE (SCHURMANS., 1991)

In most areas of the world, temperature and precipitation are perceived as the key elements of climate. Change in these elements may have a strong impact on the environment and living conditions of man. It has been shown that since 1634, the 10 'years average winter temperature at De Bilt in Netherlands has increased by 2,38 °C. On a larger scale the northern hemispheric and global surface air temperature for the 1861-1988 period has increased by 0,39 °C. Although still controversial, this increasing temperature trend is explained by enhanced greenhouse warming.

1.2- WHAT IS THE "GREENHOUSE EFFECT"

(WARRICK et al, 1990)

It is the worldwide changes in climate and sea-levels caused by a warming of the atmosphere due to the release of trace gases (ALLABY, 1988). Carbon dioxide, water vapour and certain other trace gases (such as methane) are relatively transparent to incoming short-wave radiation from the sun, but absorb long wave radiation emitted from the Earth. Then they reradiate it in all directions some downwards and some to the side were it may encounter other molecules of these gases and continue the process (see figure 1). The natural presence of such "radiatively-active" gases in the atmosphere is beneficial; they effectively "capture" heat in the lower atmosphere, thus creating a global environment which is far warmer and more hospitable than would otherwise be the case. By increasing the concentrations of greenhouse gases, the Earth's radiation balance is upset. With such a change in "radiative forcing", additional infrared radiation is absorbed in the lower atmosphere, i.e in the troposphere. This additional radiation is re-emitted and a large portion is sent back to the Earth's surface. This creates a radiative imbalance, which the system can only restore through warming of the troposphere. Among the greenhouse gases the most important anthropogenic ones are CO_2 then methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs).

Why study methane?

The analysis of air bubbles trapped in old ice from glaciers show that methane level prior to 1700 was only about 0.7 ppmV. At the present time, it is around 1.8 ppmV. During the past years, the tropospheric methane concentration has been increasing at a relative rate of nearly 1% a year and as its atmospheric lifetime is about 10 years, there is a 10% worldwide excess of sources over sinks (ROWLAND et al, 1990). Moreover, LASHOF et al in 1990, found that methane has, per mole, a global warming potential 3.7 times that of carbon dioxide.

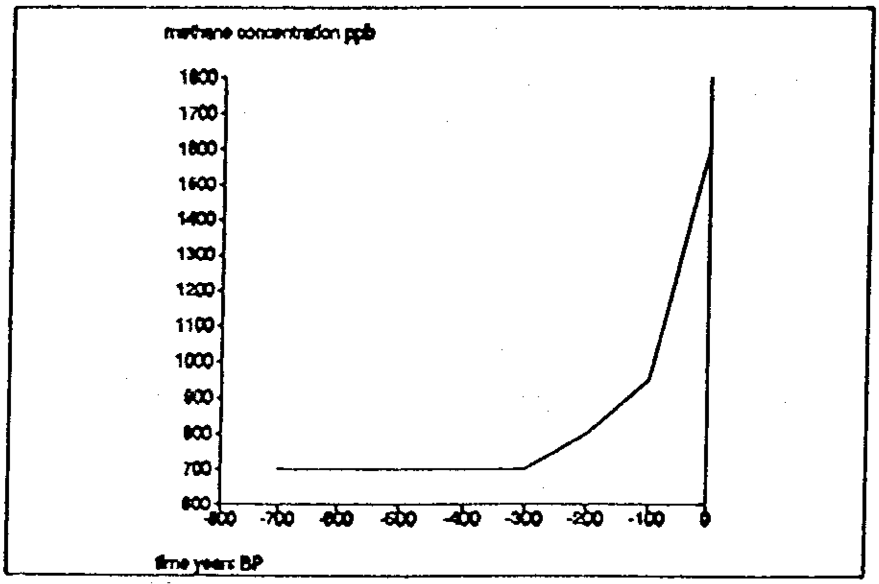


Figure1: The increase in methane concentration over the last 200 years

1.3-EFFECTS OF METHANE EMISSIONS ON ATMOSPHERIC COMPOSITION

(ROBERTSON et al, 1989)

Increased emissions of methane lead to less OH as OH is consumed in reactions with CH_4 to form ultimately CO_2 and H_2O with CO as an intermediate product.

Because CO is produced from CH_4 oxidation and is lost from the atmosphere by reaction with OH, CO also increases in the atmosphere.

As OH is lost by reaction with CO, atmospheric OH concentrations are further depressed, allowing even more CH_4 in the atmosphere to increase because of the lack of chemicals reactions with OH.

So, methane emissions in the atmosphere lead to an imbalance between OH and CH_4, and CO, which leads to larger CH_4 concentration in the atmosphere.

Burning biomass in the presence of inadequate oxygen also produces methane. Methane concentration have been detected in the atmosphere coal mine.

Ocean and freshwaters are a minor source of methane, as the open water bodies are slightly supersaturated in methane with respect to its partial pressure in the atmosphere.

Methane is also 75% of natural gas and leakage from drilling, venting or transmission, adds to the atmospheric concentration (WALLIS K.M., 1990).

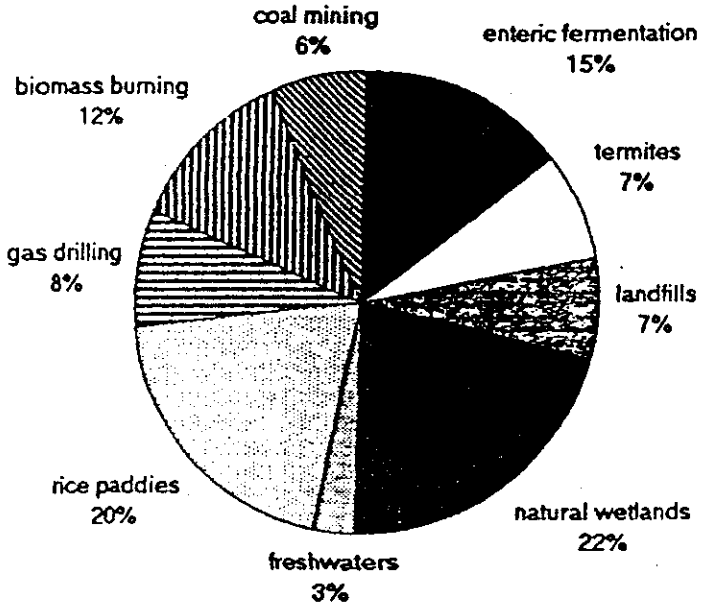


Figure 2: Sources of methane

2.2- METHANE EXCHANGE BETWEEN TERRESTRIAL ECOSYSTEM AND THE ATMOSPHERE

(CONRAD., 1989)

The various controls of methane production and emission depend on the structure of the ecosystem and of the microbial communities within.

Methane emission from a particularly ecosystem is controlled by the net balance between CH_4 production and CH_4 oxidation, only the non-oxidized part of CH_4 will enter the atmosphere.

- CH_4-producing bacteria called methanogens require strictly anoxic conditions
- CH_4-oxidising bacteria called methanotrophs require oxygen for metabolism

The methanotrophs need O_2 as an electron acceptor and cannot use others:

$$CH_4 + 3/2\ O_2 \text{ ----- } CO_2 + H_2O$$

So, the major factor controlling the CH_4-oxidization is the availability of O_2 in the area.

Methane formed in anoxic environments must pass through the oxic/anoxic boundary before entering the troposphere and the diffusion depends on the size or thickness of the path and the methane production rate.

If CH_4-production rates are too small for bubble formation or if the ebullition is hindered by a high hydrostatic pressure, there is a good chance that the upward-diffusing CH_4 is completely oxidized. A highly CH_4-productive soil can produce so much CH_4 that it forms gas bubbles which pass through the oxic layer and there is little chance for CH_4 to be reoxidized by the methanotrophs. If non-oxidized CH_4 is not getting away by bubbling gas or diffusion it can get out to the atmosphere through aquatic plants.

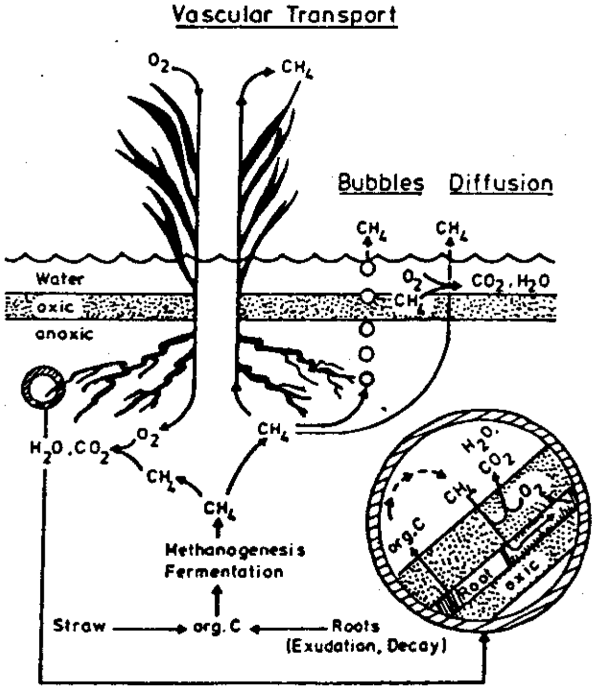


Figure 3: Process of methane release into the atmosphere: ebullition, diffusion, transport through aquatic plants

2.3-BIOLOGICAL SINKS:(PEARCE , 1990).

There are two main sinks for methane:

- oxidizing bacteria from marine sediments and soil
- photochemical decomposition in the atmosphere

Methane exchanges are summarized in the figure below.

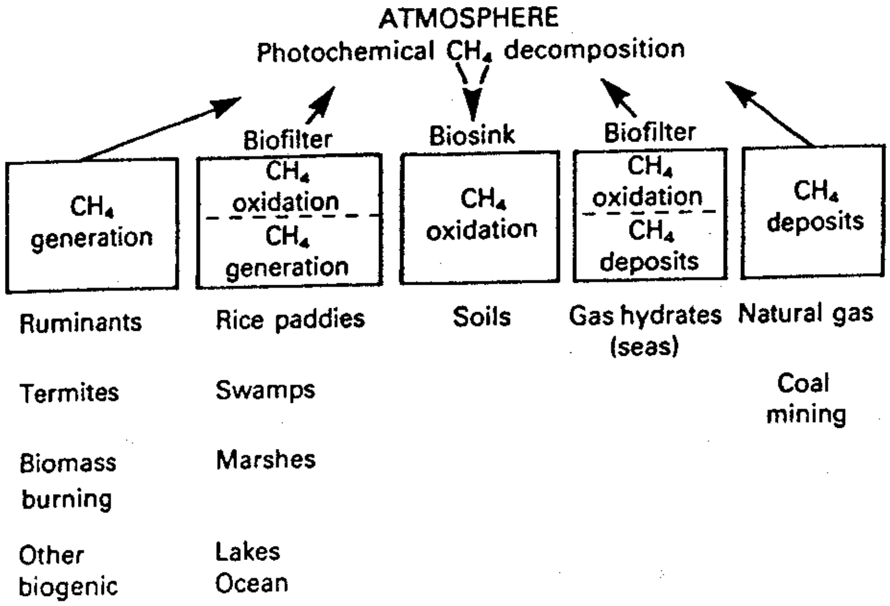


Figure 4: Sources and sinks of methane

3) ECOLOGY OF METHANOGENESIS

Under anaerobic conditions, organic matter is degraded to the gaseous end products CO_2 and CH_4.

$$C_6H_{12}O_6 \dashrightarrow 3\ CO_2 + 3\ CH_4$$

(CONRAD, 1989)

But no single microbial species is able to accomplish this reaction on its own. Methanogens, in particular can only use a limited number of very simple compounds (VOGELS et al, 1988).
So methanogenesis is done in a substrate food chain, where the fermentation end products excreted by one bacterium are utilized by another one until the organic matter is finally broken down to substrates which can be utilized by methanogens to form CH_4 as an end product (CONRAD, 1989) (see figure 5).

Methanogenesis requires interactions between nonmethanogenic bacteria and methanogens because the nonmethanogenic end products are the metabolic which methanogens use. Moreover, the environment factors required for methanogenesis must comply with both methanogenic and nonmethanogenic population (BOONE D.R., 1991)

Methanogens require an extremely anaerobic environment because O_2 inhibits methanogenesis by its toxic effects on methanogens and in addition, O_2 stimulates the activity of bacteria which can out- compete methanogens. Electron acceptors other than O_2,including nitrate, ferric and sulfate ion can also stimulate activity of organisms which can compete with methanogens (BOONE ., 1991) . Methanogens require a redox potential of -200 mV or lower to produce methane (CONRAD., 1989).

A number of environmental factors influence rates of methanogenesis including temperature, pH and the presence of nutrients (BOONE., 1985).

- pH values near neutral are considered optimal for anaerobic digestion (BOONE., 1985).
- Methanogenic rates of anaerobic digesters generally increase with temperature up to about 60°C which rates doubling for each 10°C temperature increase. (BOONE., 1985).
- Nutrients available are N, P, S, K and trace elements (HARRISS et al, 1985). Recent studies in the USA suggest that nitrogen fertilizer applied to soils may reduce the ability of soils to oxidize methane (PEARCE., 1989).

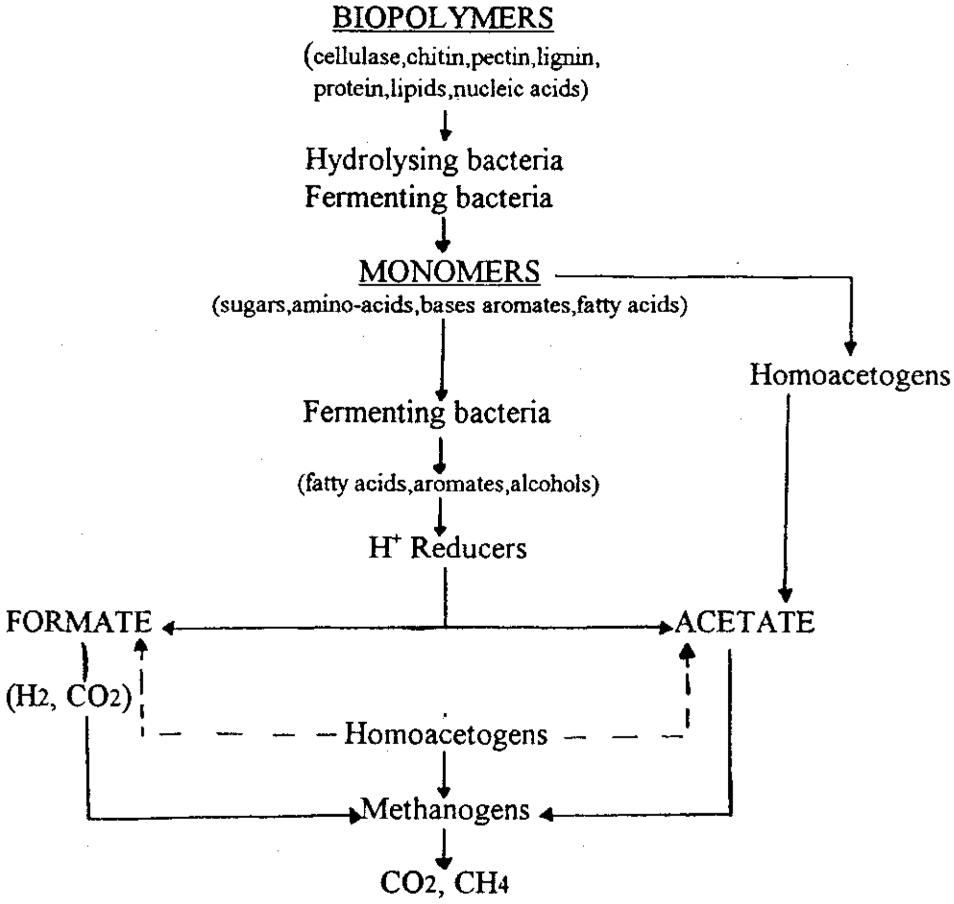


Figure 5: Anaerobic degradation of organic matter by methane producing microbial communities

4) METHANE FLUXES FROM TERRESTRIAL WETLANDS ENVIRONMENTS

(CRILL et al, 1991)

Methane fluxes from wetlands vary with latitude. In high latitude wetlands (which is the subject of this project), CH_4 fluxes are a seasonal feature because during winter the CH_4 production zone freezes. When surface organic soils are saturated with water, CH_4 production begins and rises as temperature increases, following the spring thaw .

Increased temperature leads to increase CH_4 production. The wetter sites support higher CH4 fluxes.
Concerning transport, three can be found: diffusion, ebullition and transport by rooted macrophytes.

* Higest fluxes are associated with ebullition
* Plant mediated transport supports fluxes higher than a diffusing alone
* Diffusive flux is influenced by wind velocity, by surface roughness and by limnological factors such as density stratification dynamics which can limit "dissolved CH_4 transport" to the surface.

As methanogens cannot compete for organic substrates in the presence of mineral electron acceptors (i.e. iron, manganese, nitrate and sulfate) CH_4 fluxes are usually lower from high sulfate environments such as salt marshes.
Therefore anthropogenic loading, especially of nitrate and sulfate on wetlands may have potentially serious effects on patterns of organic carbon remineralization. A change in nutrient status will change the vegetation, which will have an effect on the methane exchange rate.

Chapter 2: MATERIALS AND METHODS

-1- MATERIALS

-1.1- OPEN TOP CHAMBER

For this experiment, the peat was placed in an open top chamber. It is an open-top octagonal aluminium framed glasshouse. For this experiment, rainfall was excluded using a polyethylene ceiling fixed inside the chamber with a central drain to divert rainwater out of the chamber. This was done in order to control the water table in each peat core. In the chamber, ambient air was supplied by a pump unit providing 2 air changes per minute. The pressure from the fan minimised the amount of air which entered the chamber through the open top.

Open top chambers offered a controlled environment that enable fluxes of methane to be easily measured in semi-controlled conditions. However, the environment within the open top chamber was inevitably modified by the ambient conditions (with the enclosures and air delivery system). The main point was that the environmental conditions were homogenous above the peat buckets.

-1.2-PEAT

Three types of peat were extracted from North West Scotland in a clear air site near Kinlochbervie, Sutherland. Then they were placed in 30 litres identical polypropylene cylinders (0.31 m diameter, 0.4 m deep) . The cylinders were then, sunk into the sand in an open top chamber : there are 35 cylinders per chamber.

The three types of peat can be distinguished as follows:

TYPE OF PEAT	HEIGHT OF WATER TABLE	TYPICAL VEGETATION
pool	at the surface	bog bean
lawn	5 cm below surface	cotton grass
hummock	10 cm below surface	heather

Peat cylinders were watered daily with dionised water to maintain the height of water table to the level expected in the field conditions. Tap water was not used because its high calcium content would damage the vegetation in the cores.

-1.3- THERMOCOUPLE

Temperature was measured using a thermocouple placed in one bucket of each peat type. The reading was made just before the methane measurement of that particular peat type core. It was important to insert the pole into the same place and depth within each core. There were 4 probes on the pole which were placed at different depths: surface, 5 cm, 10 cm and 15 cm from the peat surface, in order to make a temperature profile. The same bucket was used each time for temperature measurement to ensure a continuity in the results. The thermocouple was connected to a datalogger which provided one measurement each minute.

-1.4- FLUX CHAMBERS

(see figure 6)

To measure methane a flux chamber was used. It consists of a white cylinder which fitted over the polypropylene buckets with peat. The chambers had a mixing fan and a pump which sample air above the peat. The flux chamber had to fit closely to the bucket because any leaks would have influenced the flux measurement (methane would have been diluted).

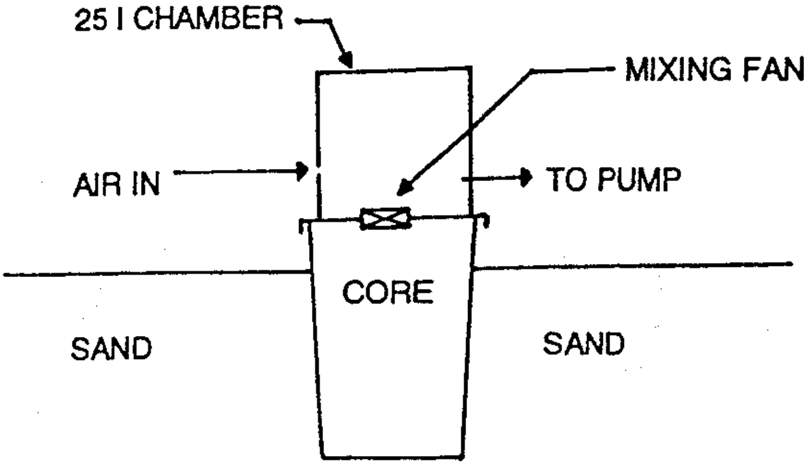


Fig 6: Cross section through a flux chamber

-1.5- DETECTION

The gas sample from the flux chamber passed through a tube of Drierite crystals to remove water vapour in the sample. Any water vapour would have influenced the methane concentration in the sample gas and could also have damaged the gas chromatograph.
The detection and assessment of the amount of methane was done using a gas chromatograph (Carlo Erba Instruments) with a flame ionisation detector (FID).
A catalytic oxidiser made from platinum was kept in the GC oven at 190°C. The catalyst and oven temperature have been optimised to destroy all of the non-methane hydrocarbons. The concentration of methane in the sample was detected with the FID in the GC, which consists of 2 electrodes : one was a metal jet and the other one had the form of a metal collar which surrounded the jet flame. Between these two electrodes a potential voltage was applied.
The methane coming from the column was mixed with hydrogen and the resulting mixture is then burnt in air. As it burned in the flame, positive ions and electrons were produced and consequently, a higher current passed between the 2 electrodes. The current was proportional to the amount of carbon content in the sample and so provided a measurement of the methane concentration. The current was then converted into a voltage which was detected using a chart recorder and datalogger. The datalogger calculated the mean voltage for every minute and you could display it on a computer. With this instrument, it took at least 10 minutes to get a steady flux value.

-2- METHODS

The GC-FID provided mV signal which need to be converted into methane concentration units ($\mu g/m^3$) after calibration:

- pure air without any hydrocarbons was injected to provide a zero value
- then, standard gas with 3.4 ppm methane concentration provided the second calibration point.

In this way, the difference between the 0 and 3.4 data in mV divided by the 3.4 ppm, was the value for the day expressed into mV/ppm.

The concentration in the ambient air entering the chamber was measured for each core sample: the flux emitted by one core was the difference between the core flux and the ambient one. It was important to be measured before each core because the ambient concentration was not always the same during the day. Four same peat type cores were sampled consecutively, then four cores from another peat type and so on... In this way, the thermocouple was not moved each time which avoid disturbing the core each time. Besides the cores used for the temperature measures were not sampled.

For each core the height of water table was assessed.

The flux was determined with the following equation:

$$F= [\ V(X_i - X_0)]\ A^{-1}$$

where: F= methane flux $mg/m^{-2}/s^{-1}$
V= flow rate m^{-3}/s^{-1}
X_0= methane concentration inside the chamber mg/m^{-3}
X_i= ambient methane concentration mg/m^{-3}
A= area of core = 0.0707 m^2

The flow rate was measured using a bubble meter: it is a 2 litres glass column with a soap film. The air flow from the flux chamber was inserted into the column and the flow rate was measured from the average time needed for one bubble to pass the 1 litre gap.

Using this technique, the dependence of methane emissions on temperature and water levels can studied for each of the three peat types.

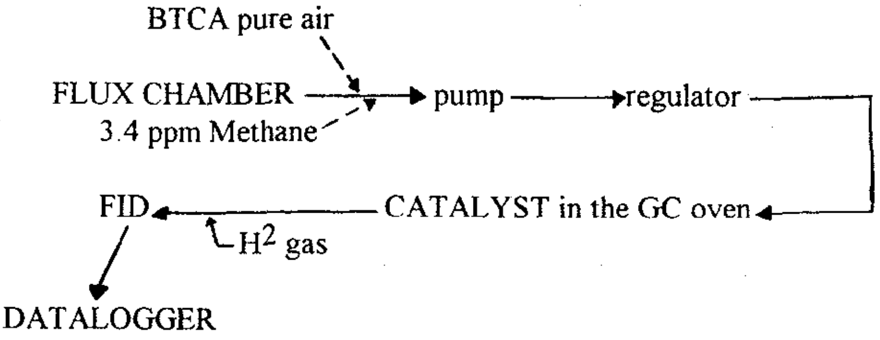


Fig 7 : The experimental set up

Chapter 3 : RESULTS

-1- GENERALITIES

The results obtained showed that there were differences in methane emissions between the hummock peat type, the lawn and pool. Among the 35 pool measurements, the 32 lawn measurements and the 29 hummock, the average emissions in $\mu g/m^{-2}/s^{-1}$ were the following:

	POOL	LAWN	HUMMOCK
Mean	0.5834	0.4053	0.1059
Minimum	0.0847	0.0408	-0.0548
Maximum	1.4363	1.0516	0.4139
Standard deviation	0.36	0.3059	4.26

As far as we are comparing the three types, it is clear that the hummock peat has a large standard deviation and is also the only peat to show negative fluxes (methane uptake). The average for pool and lawn are quite similar and as the standard deviation was quite the same, a Mann-Whitney test was done to compare the 2 populations whether they would be significantly different or not. Minitab Software showed that they were significantly different with a 0.05% probability error (see appendix 1).

Lawn, hummock and pool have therefore significantly different methane emissions where pool has the highest ones, hummock, the lowest, and is consistent with the previous data obtained by HARGREAVES and FOWLER, (1992).

-2-METHANE EMISSIONS AND TEMPERATURE

Previous data obtained showed a link between methane emissions and the core temperature at 5 cm depth, for the three peat types.

We can see on graphs 8a)b)and c) a clear correlation between methane emissions and temperature at 5 cm depth in pool and lawn. Hummock peat shows a line near the horizontal which means we can not detect any correlation; the data are too scattered. To be more precise, a regression was calculated on Lotus 1.2.3. for each peat type with methane emissions versus temperature at 5cm, 10cm, 15cm depth. The results are collected in the Appendix 2.

It can be seen that with the number of observations in each peat type, the correlation between the temperature and methane emissions is only significant with the pool and lawn. Methane emissions from hummock peat are not correlated with temperature. Moreover, the correlation for the pool and lawn peat are significant at 5, 10 and 15 cm temperature depth (see graphs in Appendix 3). This results is quite different from the previous data obtained where only the 5 cm depth temperature was correlated with methane emissions.

Fig 8a: METHANE VERSUS TEMPERATURE IN POOL TYPE (5 cm depth)

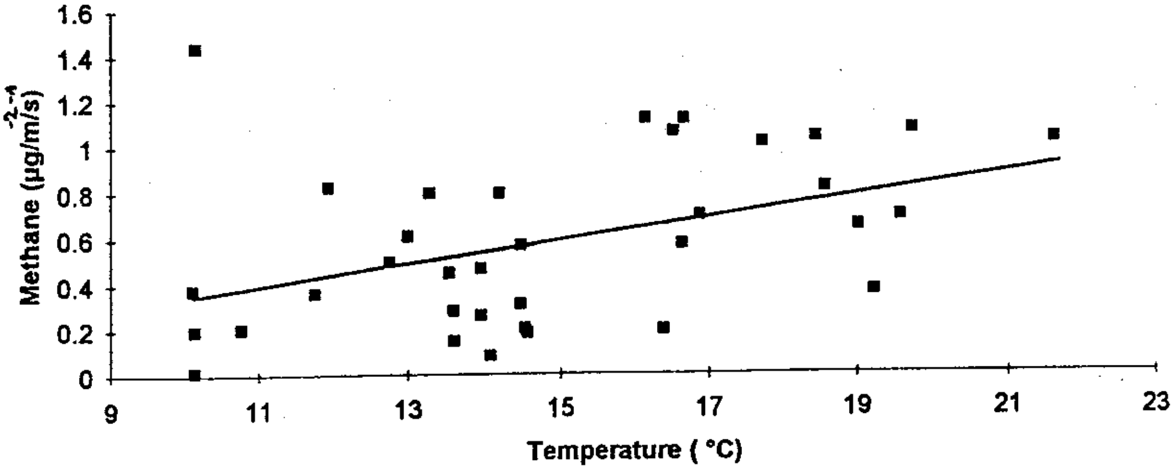


Fig 8b: METHANE VERSUS TEMPERATURE IN LAWN TYPE (at 5 cm depth)

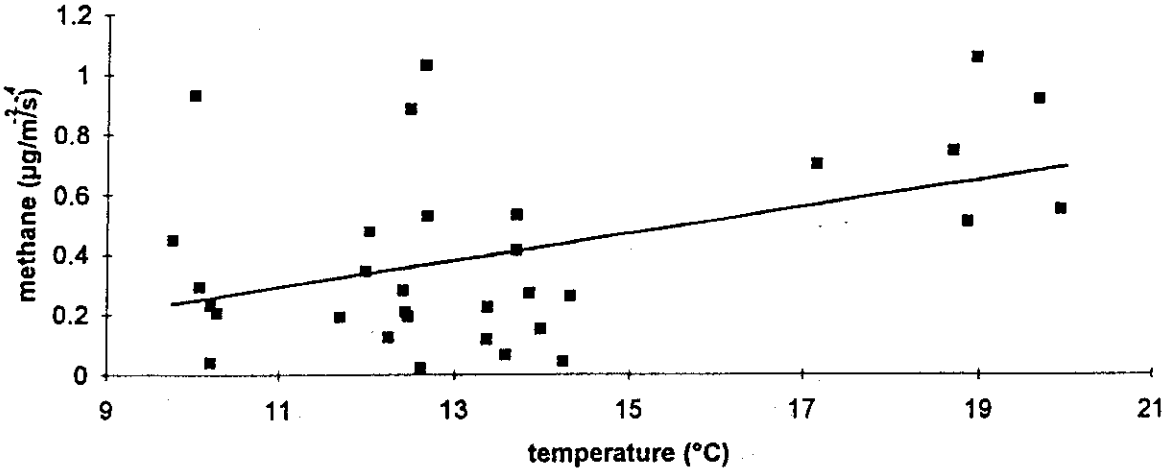
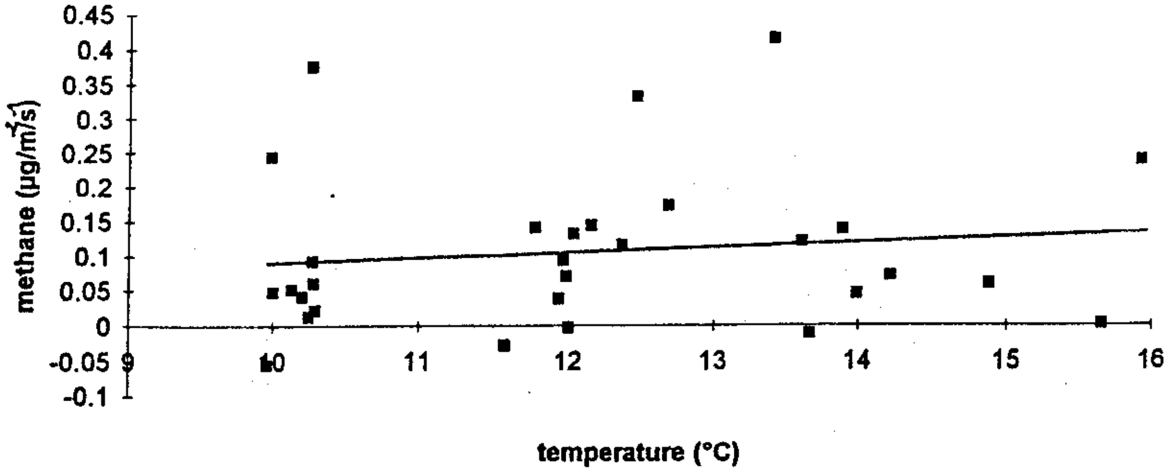


Fig 8c: METHANE VERSUS TEMPERATURE IN HUMMOCK TYPE (5 cm depth)



The data showed considerable scatter in methane emission for the pool, lawn and hummock peat whatever the temperature was. By looking at the core numbers on each graph it was pointed out that some cores emit less methane than others at all temperature and on the opposite some cores emit more than others. So the variability in emission between the core was largely responsible, for the lack of correlation between temperature and methane emissions. At the same time, the correlation for the pool and lawn peat would be even more significant without the core variability.
Being informed of that variability, it was decided to study just one core for the water level experiment which follows.

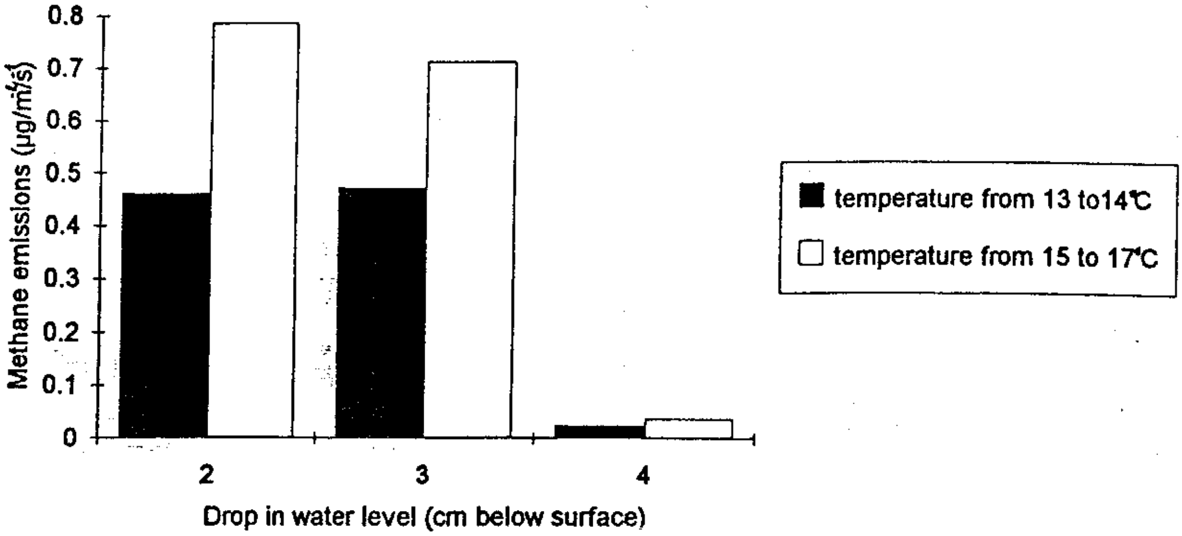
-2-.METHANE EMISSIONS AND DEPTH OF WATER TABLE

The effect of the water table depth was also studied. One pool core with an average temperature response corresponding to its type was chosen. As core 24 followed the regression plot quite well we studied it. The same choice was done on a hummock core; even if the regression plot was not significant, the core 26 was among the main part of the data for 3 different temperatures.

In order to see the water level effect, the core 24 was dried as much as possible and the core 26 was abundantly watered.
Core 26 received 1.5 litre on the first day of the experiment to raise the water table from 13cm to 9 cm below surface and then .0.7 litre on the third day to increase the water level from 9 cm to 3 cm below.
Between each watering the methane emissions were measured in the morning and in the afternoon to have two temperatures ranges. Methane emissions from core 24 were assessed in the same way as it was getting drier and drier.
The temperatures in the morning and in the afternoon needed to be very close among the days to be sure that the variations of methane emissions would only be monitored by the drop or increase in water level. The morning temperatures ranged from 13 to 14°C in the pool core, 12 to 13°C in the hummock core, and the afternoon temperatures ranged from 15 to 17°C in the pool core and 14 to 15°C in the hummock core at 5 cm depth.

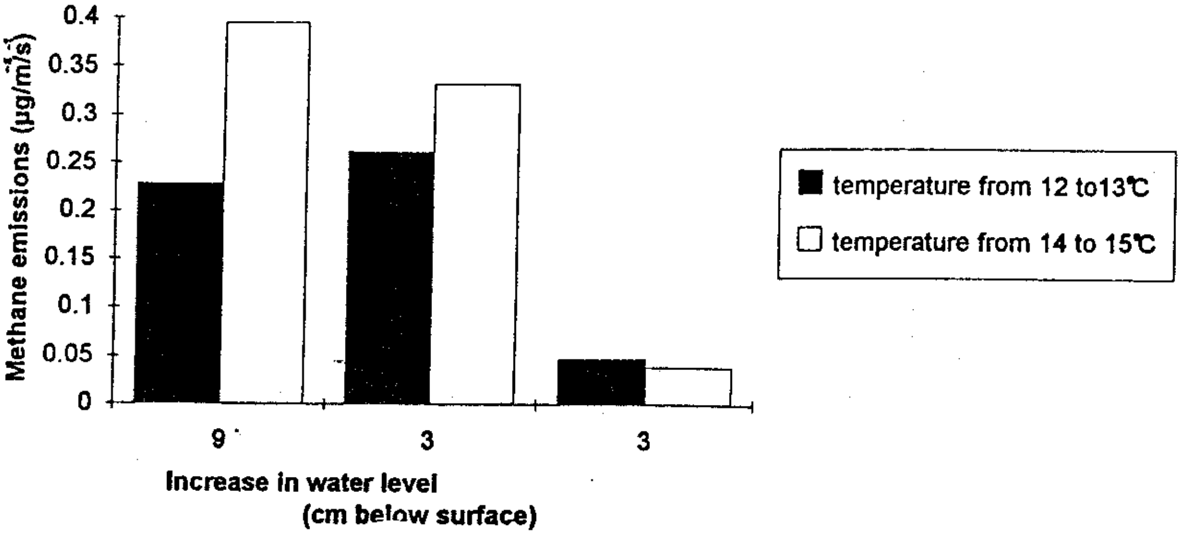
After one week, core 24 had dried to 4cm below surface (water could not be seen on the bucket edges). The 6 measurements showed a decrease after 6 days without water supplies (95 % decrease in methane emission). The effect of a temperature rise on methane emissions could also be detected between the morning and the afternoon data (see graph 9a).

Fig 9a): METHANE EMISSIONS VERSUS DROP IN WATER LEVEL (pool n°24)



After one week, core 26 was wet within the whole core. During the 2 different stages of watering, no methane emissions gradient could be observed, only a decrease with the last data could be viewed. The variation of methane emissions with temperature range was confirmed (see graph 9b).

Fig 9b): METHANE EMISSIONS VERSUS INCREASE IN WATER LEVEL (hummock n°26)



Chapter 4 : DISCUSSION

1- VARIATION OF METHANE EMISSIONS WITHIN POOL, LAWN AND HUMMOCK PEAT

The results obtained showed a clear difference among pool, lawn and hummock peat. These variations may be explained by taking into account the microbial activities of the methanogenic bacteria within the peat core. The CH_4-producing bacteria (methanogens) require strictly anoxic conditions which are provided in a pool core.
On the other hand, the CH_4-oxidising bacteria (methanotrophs) require oxygen for metabolism which is provided in the hummock peat dry layer.

Therefore, the different fluxes among the three peat types could be explained with the height of water level in each peat. Pool had a very high moisture level therefore anaerobic conditions to favour methanogens. Hummock had at least, a 8cm oxidised layer where methane could be oxidised by methanotrophs. Lawn had a thinner oxidised layer where methane could sometimes diffused without being oxidised.

The negative fluxes observed in a few hummock cores (all different each time) were the result of a high methanotroph activity that led to a methane uptake by the core; just a very little methane flux was emitted from the cores.

-2- VARIATION OF METHANE EMISSION WITH TEMPERATURE

-2.1- HUMMOCK peat

Methane fluxes from hummock peat were not correlated with temperature. The values were very scattered and could be explained by the high variability in water table among the hummock peat. It ranged from 5 to 13 cm below surface.
That variability meant really different oxidising in the cores and different methanotroph activity . Hummock peat showed high interactions between methanotrophs and methanogenic bacteria which activities towards temperature were then difficult to quantify.

The 8 hummock cores available provided the largest flux variability while the 10 pool cores available provided the lowest. With this variability, it is not surprising that no correlation between the hummock cores and temperature was detected, many more measurements would have been required.

-2.2- POOL and LAWN peat

Methane emissions from those two peat types were significantly correlated with temperature, methane emissions increased with temperature. The microbial activities are therefore enhanced by temperature. If other than temperature, all the environmental factors remained constant, a warming climate would increase the methane emissions to the atmosphere.

The correlation with temperature was concluded whatever the depth where temperature was measured. This is different from the previous data obtained where only the temperature at 5 cm depth was significantly correlated with methane emissions.

Two explanations were expressed:

- either the soil temperature at 5, 10 and 15cm are not different enough to make CH_4 emissions vary.
- or, there were not enough measurements to extract the depth at which temperature has the maximum effect.

As the temperature data measured each day were not from the same core (the thermocouple was moved at each change in peat type) it was not possible to study the variations in the core temperatures at 5, 10 and 15cm depth. Therefore data from field experiment on September 1991 were used. They were chosen to be the closest to the temperature profile obtained in the cores. In order to see the general evolution three graphs were made for each peat type on a 24 hours measurement (see Appendix 4).

It could be seen that there was a difference between each depth at any time. The data from field experiment ranged from 5cm to 40cm below surface and as for the comparison with core from the open top chamber, only the temperature range from 5 to 15cm was necessary, the graph 10a)b)and c) were made with only the 5 and 10cm depth.

Fig 10a): EVOLUTION OF SOIL TEMPERATURE IN POOL TYPE (5 and 10 cm depth)

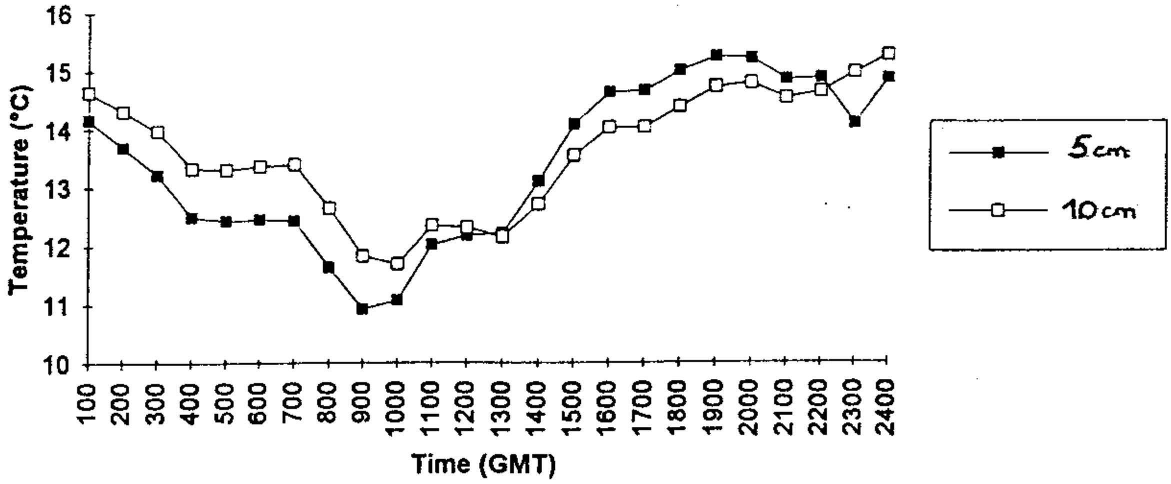


Fig 10b): EVOLUTION OF SOIL TEMPERATURE IN LAWN TYPE (5 and 10 cm depth)

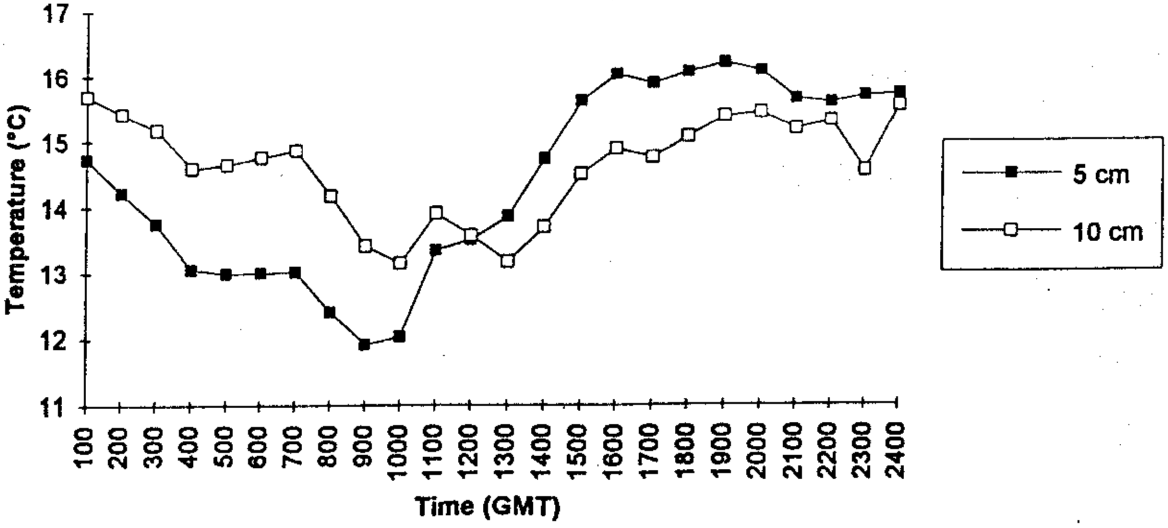
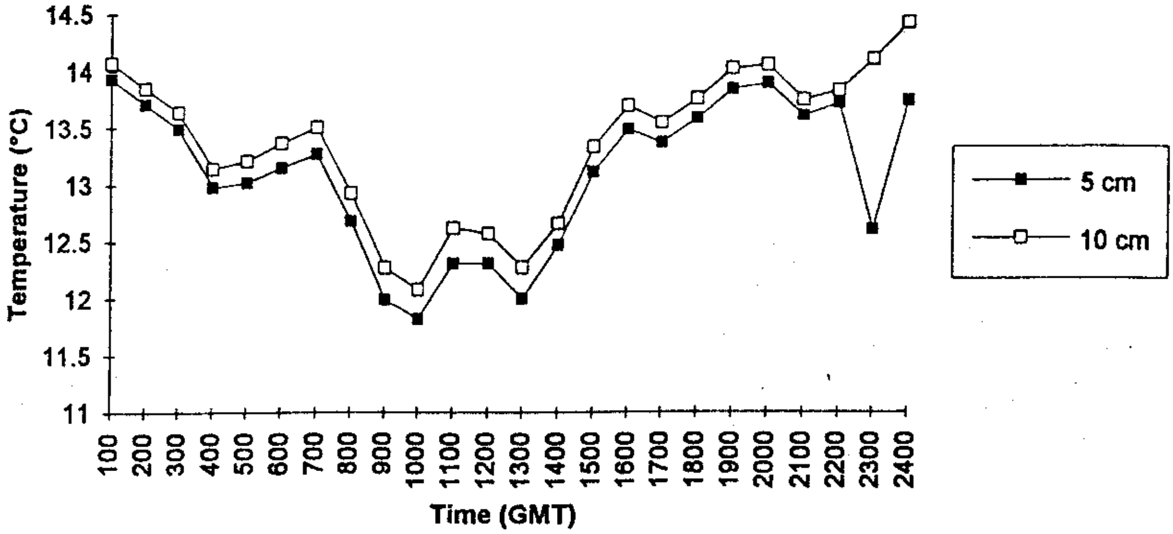


Fig 10c): EVOLUTION OF SOIL TEMPERATURE IN HUMMOCK TYPE (5 and 10 cm depth)



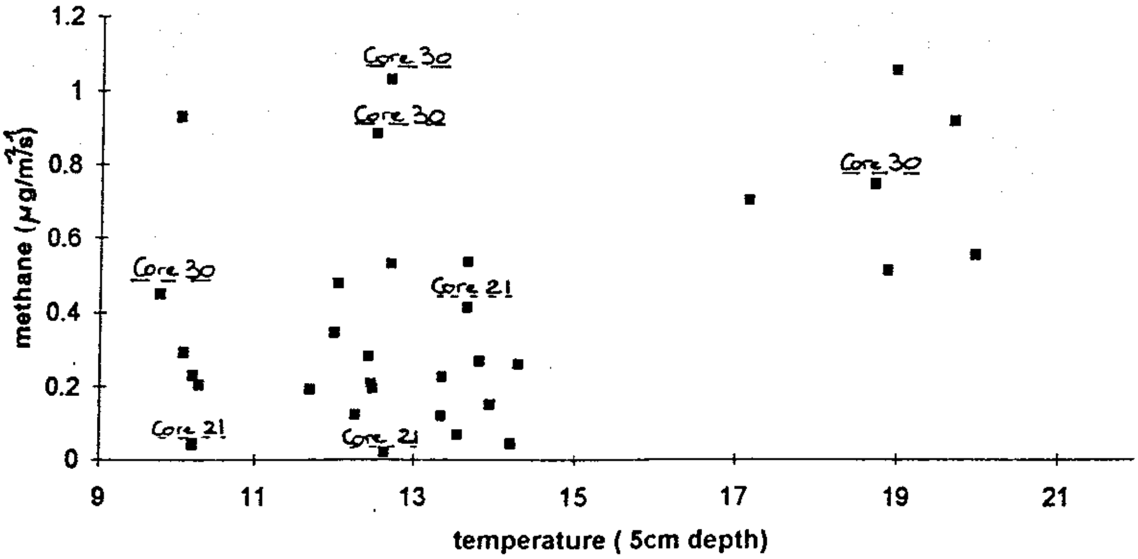
It could be seen that the difference within the depth were closer for hummock and largest for lawn. However, the difference between 5 and 10cm depth ranged from only: 0.3°C to 1.8°C. Moreover, for the hours the measurements were made (roughly 8.00 GMT to 16.00 GMT) the gap between the two were not so high, especially after 13.00.

Considering the tiny temperature deviation at 5 and 10cm depth and the few measurements made it could be concluded that the effect on methane emissions of the depth where temperature was assessed could not be detected.

-3- VARIATION OF EMISSIONS BETWEEN EACH CORE WITHIN EACH PEAT TYPE

On the graph 8a)b) and c) it was noticed that one or two cores had anomalous behaviour. For example, core n°30 and core n°21 on the figure 8 b).

Fig 8b): methane versus temperature in lawn type



By studying the characteristics of these cores it was noticed that they had different water level from these expected for a lawn type even if they had the usual vegetation. In that way, core n°30 had its water level on the surface and belonged to the highest fluxes on the graph. While, core n°21 had a very low water level for a lawn (10 cm below surface) and belonged to the lowest fluxes.

The variability within certain core could also come from a nutrient problem: when the lids are off, the cores are watered by rain which can contain $NH_4^+$and NO_3^-which may affect the microbial activity within the core.

-4- VARIATIONS OF METHANE EMISSIONS WITH WATER LEVEL

The increase and the drop in water level were assessed for only one week which was not sufficient. There is no value for the first day of experiment because the temperature was only 11.5°C in the 2 cores, not close enough to the temperature range which was after.

The pool core was affected by the drop and the emissions after 6 days drying suddenly decreased. The surface layer became dry and methanotrophs were then able to oxidise methane. However, such a fast decrease was really surprising and more measurements would be necessary to confirm the decrease.

For the hummock core, the increase in water level did not seem to affect the methane emissions for the first 2 watering. However, after 6 days, a drop in methane emissions was observed. It is possible that the increase water level could have decreased the temperature and therefore had an effect on methane emissions. Not any temperature difference was confirmed. At the same time, the increase in water level could provide a bigger anaerobic layer for methanogens to produce more methane. The results obtained seemed to be opposite to those expected pattern.

The too few measurements were made to obtain clear results.

-5- SOURCES OF ERROR

There was probably an error involved in assuming that the temperature of one peat core would be representative of all the other cores of the same type, even though all environmental factors within the open top chambers are assumed to be constant. The temperature of each individual core would depend on the intrinsic differences between the cores, the duration of time the core is exposed to sun , the water table height for examples.

Moreover, the method used to insert the thermocouple was not probably the best one to ensure a good temperature profile. Indeed, in order to avoid destroying the peat structure, the bamboo pole was not inserted in the bucket centre but on the side, very close to the plastic face. Even if the probes were not in contact with the plastic face, the environmental conditions were not as true as they would have been in the core centre.

In some cases, the flux chamber did not make a good seal with the peat core while measurements were being taken. Hence, as the pump in the flux chamber drew air from beneath it, there were probably any mixing with ambient air.

Every value is based on comparing the methane concentration inside the flux chamber (X_0) to the ambient methane concentration (X_1). The X_1 value was not steady during the whole day and did particularly decreased in the morning. A few times, a choice needed to be made between the ambient concentration before or after the flux chamber measurement. it was decided that in such a case the reading after would be chosen, as it is always the closest in time to the core concentration. This presents an error in itself.

In assessing the decrease in water table, the reading on the core was made by looking at the height of water level on the side of the bucket. But even if any level was not seen on the bucket side, that unfortunately did not mean that the peat was dry on the first 3cm; it was still wet. The method used for the drying assessment was not adequate.

-6- AREAS OF FURTHER STUDY

Methane is the second most important trace greenhouse gas after carbon dioxide. The atmospheric concentration of methane is rising at a relative rate of nearly 1% a year. Emissions from wetlands are the largest natural sources of methane to the atmosphere. Scotland has large areas of peat bogs and a better understanding of the mechanisms controlling methane emissions from wetlands is required to extrapolate emissions from cores to the landscape. This in turn will enable better estimates of global emissions to be made, and to allow predictions of the effect which changes in climate may have on emissions.

By studying the behaviour of one core to temperature and water level, an experimental model of methane emissions with temperature and water table would be made. such a model would certainly help to identify the variables (temperature or water table) that are most important in regulating in methane emissions.

Other interesting area would be the influence of added nutrients such as N, P, S, K, in the cores. A recent study in USA showed that nitrogen fertiliser applied to soils may reduce the ability of soils to oxidise methane. Nitrogen fertiliser added to the cores at different amount could perhaps cause an increase in methane emissions.

The function of plant vascular transport in methane release into the atmosphere is also an important area of study. The vascular transport which might occur with cotton grass is certainly more efficient than diffusion and therefore allows methane to avoid transport through an oxidised layer where it would be transformed to CO_2.

REFERENCES

1- ALLABY M.,1988, Mac Millan Dictionary of the Environment
THE MAC MILLAN Press Ltd, third edition ,LONDON.

2- BOONE D.R., 1985, Fermentation Reactions of Anaerobic Digestion, pp 41-51. In N.CHEREMISINOFF and R.P.OUELLETTE, BIOTECHNOLOGY: Applications and research. Technomic Publishing Co., Lancaster, Pa.

3- BOONE D.R., 1992, Ecology of Methanogenesis, pp 57-67. In J.E ROGERS and W.B WITHMAN, Microbial Production and Consumption of Greenhouse Gases: methane, nitrogen oxides and halomethanes. WASHINGTON D.C, American Society for Microbiology,1992.

4- CONRAD R., 1989, Control of Methane Production in Terrestrial Ecosystems. pp 39-58. In ANDREAE M.O., SCHIMEL D.S., Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere. Report of the Dalhem Workshop, BERLIN, 1989, february 19-24. John WILEY and Sons. Inc., NEW YORK.

5- CRILL P.M., HARRISS R.C., BARTLETT K.B., 1991, Methane fluxes from terrestrial wetlands environments. pp 91-105. In J.E ROGERS and W.B WITHMAN, Microbial Production and Consumption of Greenhouse Gases: methane, nitrogen oxides and halomethanes. WASHINGTON D.C, American Society for Microbiology,1992.

6- GALCHENKO V.F., LEIN A., IVANOV M., 1989, Biological Sinks of Methane. pp 59-71. In ANDREAE M.O., SCHIMEL D.S., Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere Report of the Dalhem Workshop, BERLIN, 1989, february 19-24. John WILEY and Sons. Inc., NEW YORK.

7- HARGREAVES K.J., FOWLER D., 1992, The emission of methane from UK wetlands, T07057d2 Project Report, ITE Edinburgh

8- HARRISS R.C., GORHAM E., SEBACHER D.I, BARTLETT B., FLEBBE P.A., 1985, Methane Flux from Nothern Peatlands, NATURE, 315, pp 652-653.

9- PEARCE F., 1989, "Methane, the hidden greenhouse gas", THE NEW SCIENTIST, 1663, pp 37-41.

10- ROBERTSON G.P.(rapporteur) et al, 1989, Trace Gas Exchange and the Chemical and Physical Climate: Critical Interactions. pp 303-320. In ANDREAE M.O., SCHIMEL D.S., Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere. Report of the Dalhem Workshop, BERLIN, 1989, february 19-24. John WILEY and Sons. Inc., NEW YORK.

11- ROWLAND F.S., HARRISS R.P., BLAKE R., 1990, Methane in Cities, NATURE, 347, pp 432-433.

12- SCHURMANS C.J.E., 1991, Climatic Evolution during the Last Century. pp 107-123. In DUPLESSY J.C., PONS A., FANTECHI R., Climate and Global Change. Proceedings of the European School of Climatology and Natural Hazards Course, Arles, FRANCE, from 4 to 12 April 1990. COMMISSION of the EUROPEAN COMMUNITIES, BRUSSELS.

13- VOGELS G.D., KELTJENS J.T and Van Der DRIFT, 1988, Biochemistry of Methane Production, pp 707-770. In ZHENDER A.J.B., Biology of Anaerobic Microorganisms, John WILEY and Sons. Inc., NEW YORK.

14- WALLIS K., 1990, Leaky Answer to Greenhouse Gas, NATURE, vol 344, pp 25-26.

15- WARRICH R.A., BARROW E.M., WIGLEY T.M.L., 1990, The Greenhouse Effect and its implication for the European Community. Climatic Research Unit, SCHOOL of ENVIRONMENTAL SCIENCE of EAST ANGLIA. LUXEMBOURG.

16- YAVITT J.B., LANG G.E., SEXTONE A.J., 1990, Methane Fluxes in wetland and forest soils, beaver ponds, and low-order streams of a temperate forest ecosystem. JOURNAL of GEOPHYSICAL RESEARCH, 95, 22463-22474.

17- ZIMMERMANN P.P., GREENBERG J.P., WANDIGA S.O., CRUTZEN P.J., 1982, Termites: a potentially large source of atmospheric methane, carbon dioxide and molecular hydrogen. SCIENCE, 218, pp 563-565.

APPENDIXES

APPENDIX 1 : Mann-Whitney test from Minitab software

APPENDIX 2 : Regression results

APPENDIX 3 : a) Methane emissions versus temperature at 10 cm depth in pool, lawn, hummock type.
b) Methane emissions versus temperature at 15 cm depth in pool, lawn, hummock.

APPENDIX 4 : a) Evolution of soil temperature in pool type
b) Evolution of soil temperature in lawn type
c) Evolution of soil temperature in hummock

APPENDIX 5 : a) Table of pool data
b) Table of lawn data
c) Table of hummock data
d)Table of data from core 24 and 26

APPENDIX 1

```
MTB > mann c1 c2

Mann-Whitney Confidence Interval and Test

C1      N = 35    Median =     0.5657
C2      N = 32    Median =     0.2867
Point estimate for ETA1-ETA2 is      0.1560
95.1 pct c.i. for ETA1-ETA2 is (0.0052,0.3409)
W = 1352.0
Test of ETA1 = ETA2  vs.  ETA1 n.e. ETA2 is significant at 0.0426
```

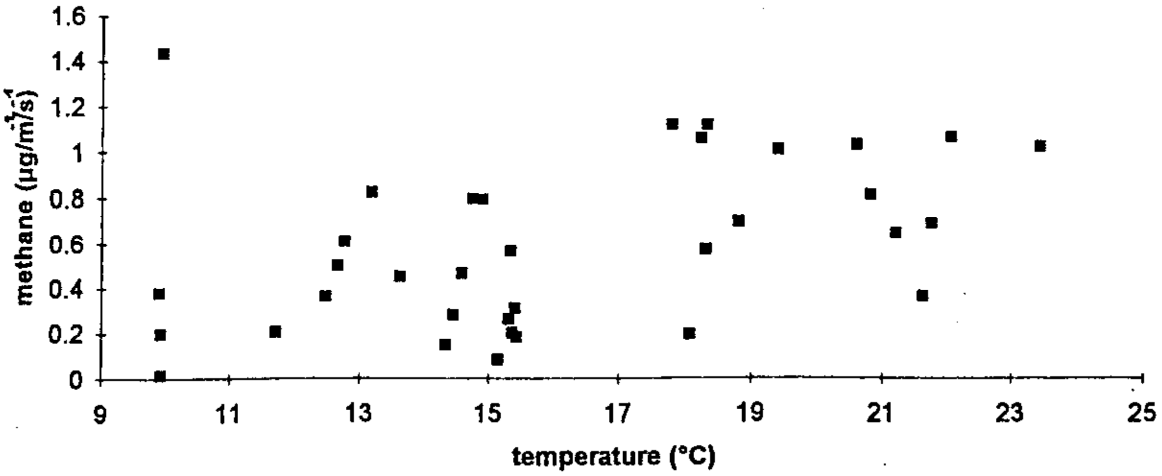
APPENDIX 2

Regression Statistics			
	[illegible]	[illegible]	[illegible]
Multiple R	0.4107	0.4268	0.1127
R Square	0.1687	0.1821	0.0127
Standard Error	0.3365	0.2812	0.1166
Observations	35	32	30
Freedom degree	33	30	28
Coefficients			
Intercept	-0.0139	-0.0199	0.0171
x1	0.0484	0.0446	0.0073
Standard Error			
x1	0.0187	0.0172	0.0121
	[illegible]	[illegible]	[illegible]
Multiple R	0.409	0.4161	0.1308
R Square	0.1673	0.1732	0.0171
Standard Error	0.3368	0.2827	0.1182
Observations	35	32	30
Freedom degree	33	30	28
Coefficients			
Intercept	-0.0415	-0.0849	0.0259
x1	0.0389	0.0336	0.0059
Standard Error			
x1	0.0151	0.0134	0.0086
	[illegible]	[illegible]	[illegible]
Multiple R	0.435	0.3946	0.1059
R Square	0.1892	0.1557	0.0112
Standard Error	0.3323	0.2857	0.1186
Observations	35	32	29
Freedom degree	33	30	27
Coefficients			
Intercept	-0.37	-0.3236	-0.0064
x1	0.0702	0.0565	0.0096
Standard Error			
x1	0.0253	0.024	0.01737

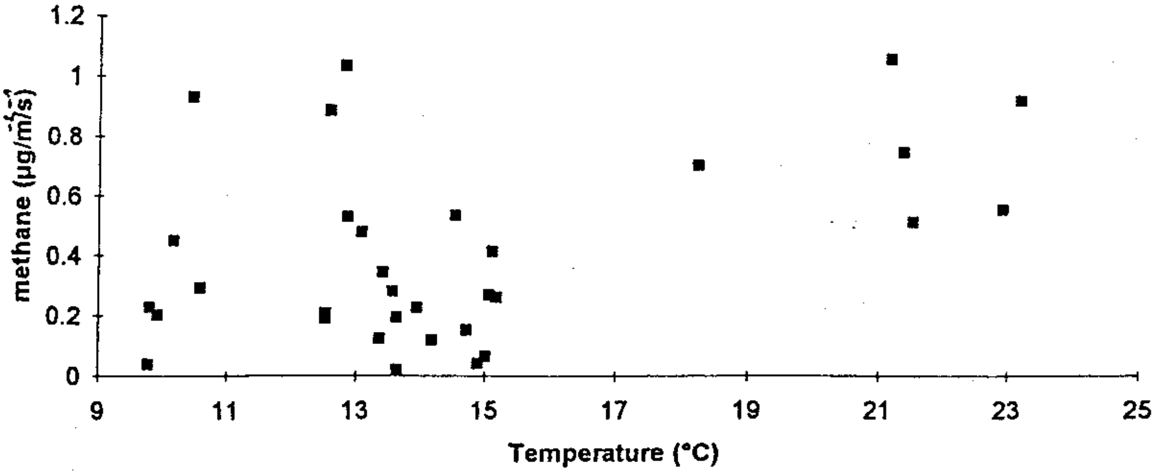
APPENDIX 3

a) Methane emissions versus temperature at
10 cm depth in pool, lawn, hummock type.
b) Methane emissions versus temperature at
15 cm depth in pool, lawn, hummock

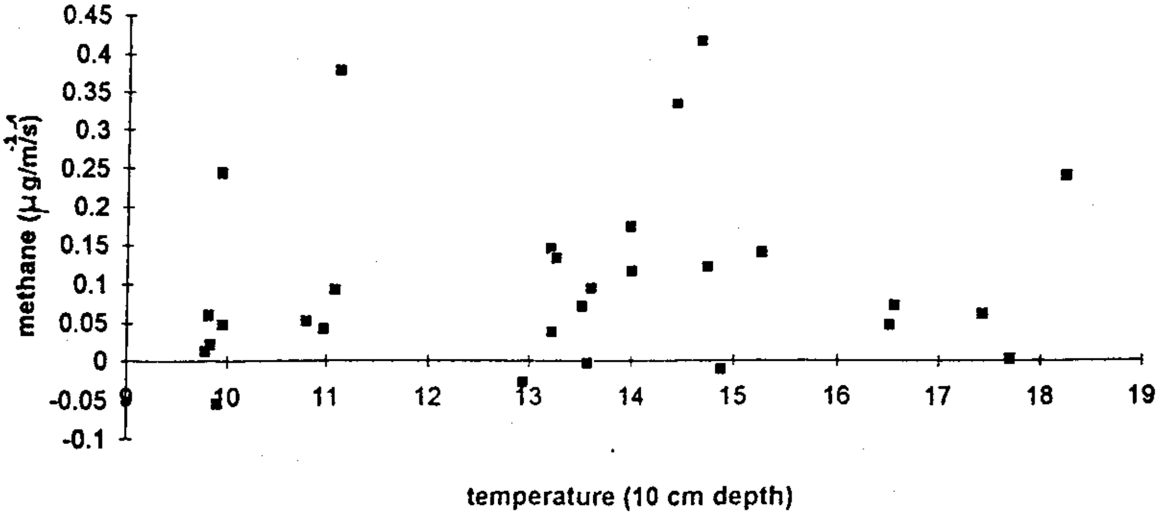
METHANE VERSUS TEMPERATURE IN POOL TYPE (10 cm depth)



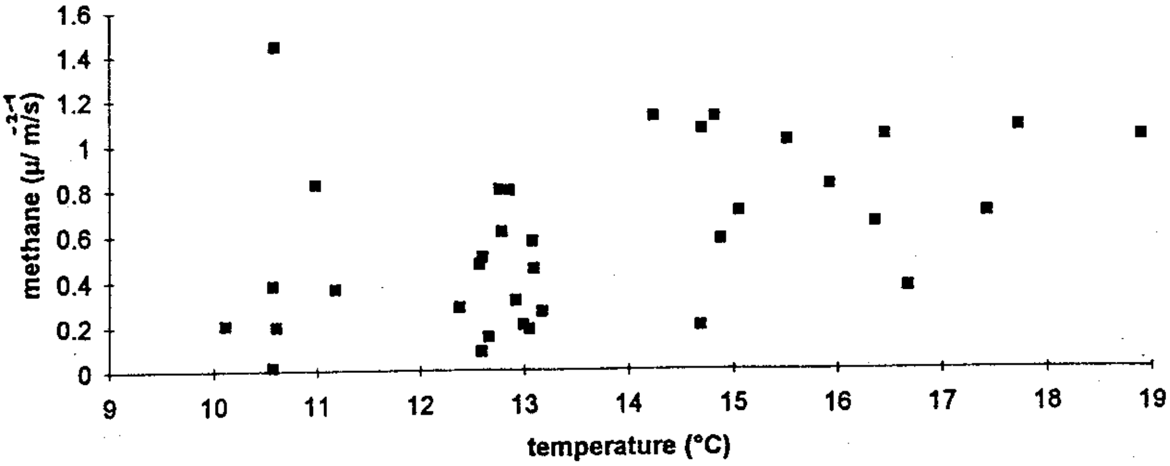
METHANE VERSUS TEMPERATURE IN LAWN TYPE (10 cm depth)



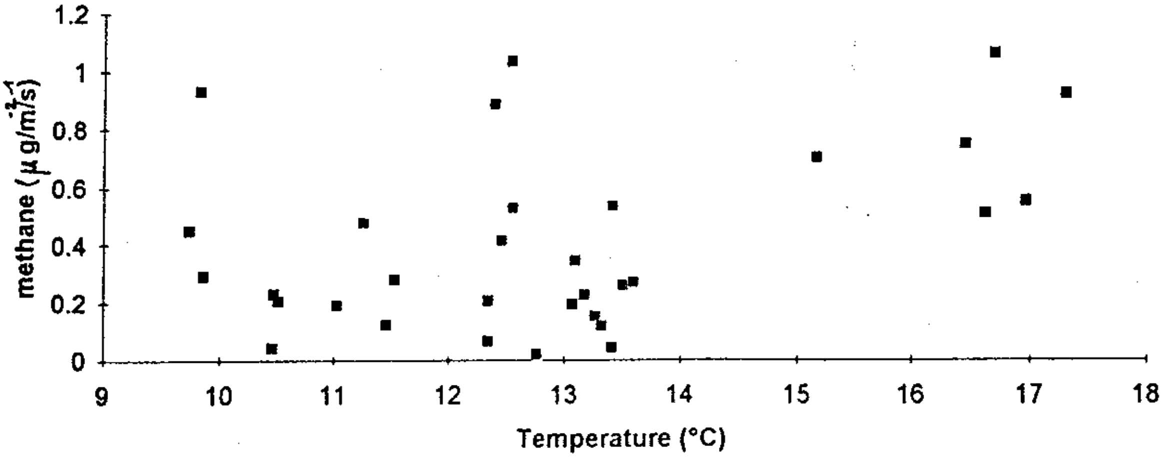
METHANE VERSUS TEMPERATURE IN HUMMOCK TYPE



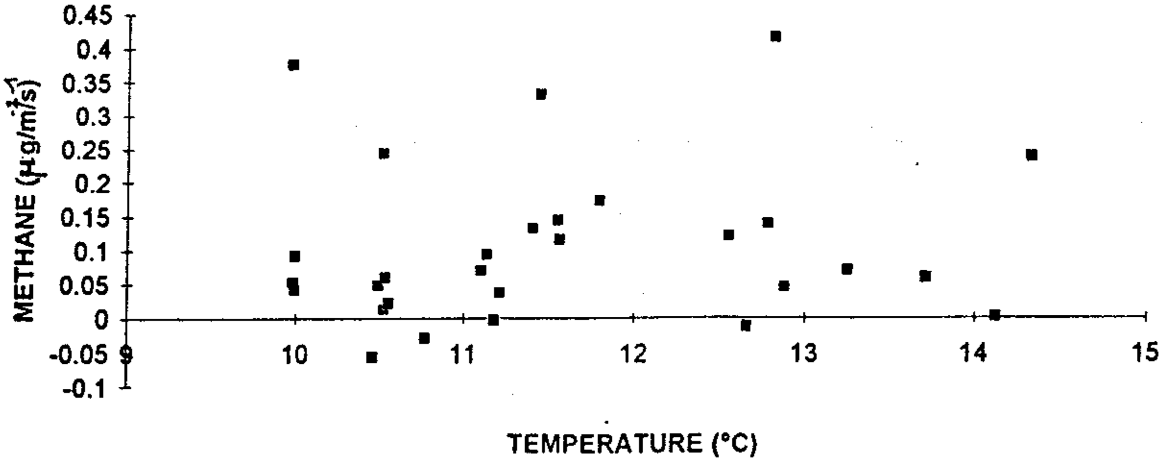
METHANE VERSUS TEMPERATURE IN POOL TYPE (15 cm depth)



METHANE VERSUS TEMPERATURE IN LAWN TYPE (15 cm depth)



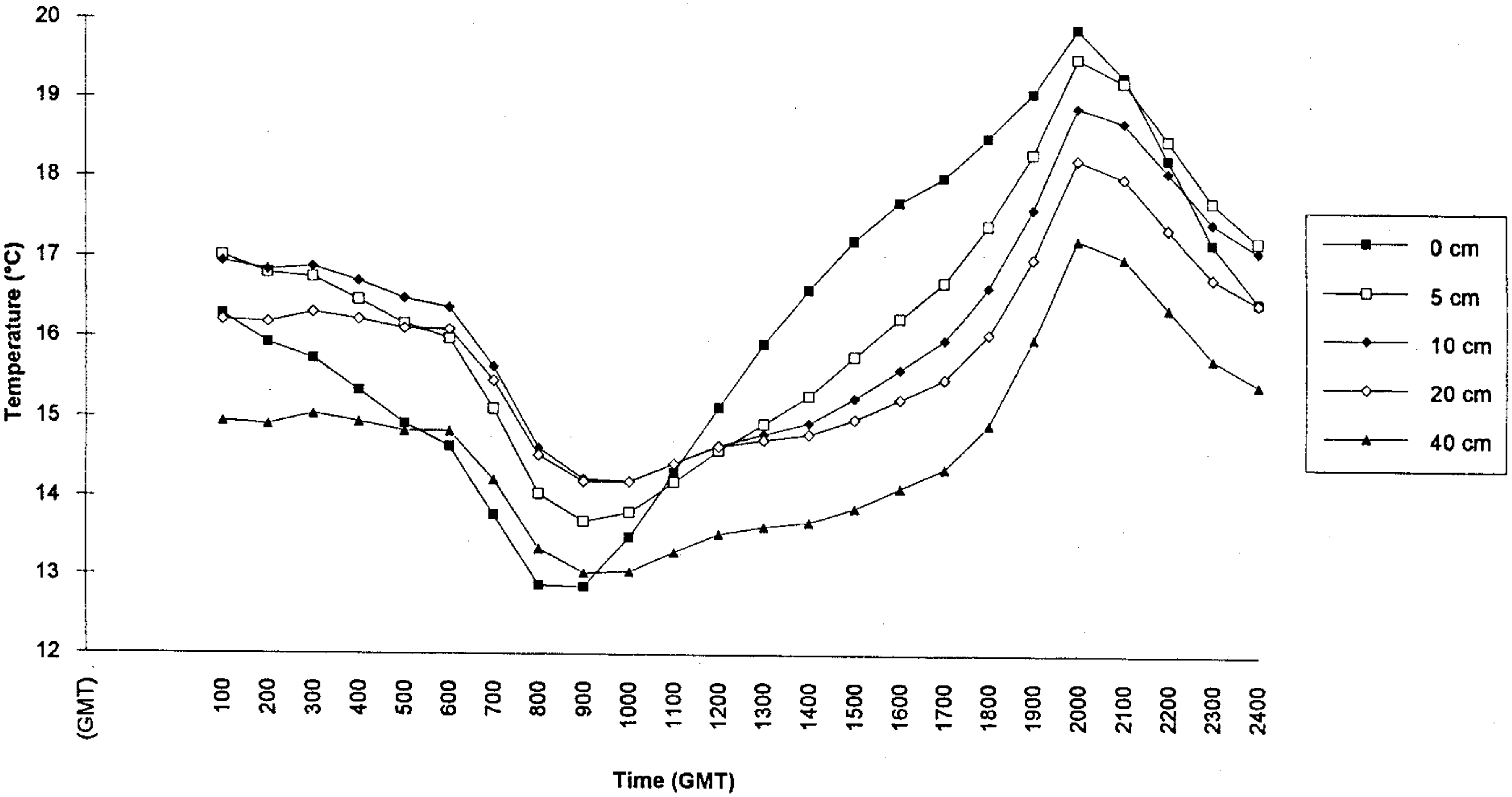
METHANE VERSUS TEMPERATURE IN HUMMOCK TYPE (15 cm depth)



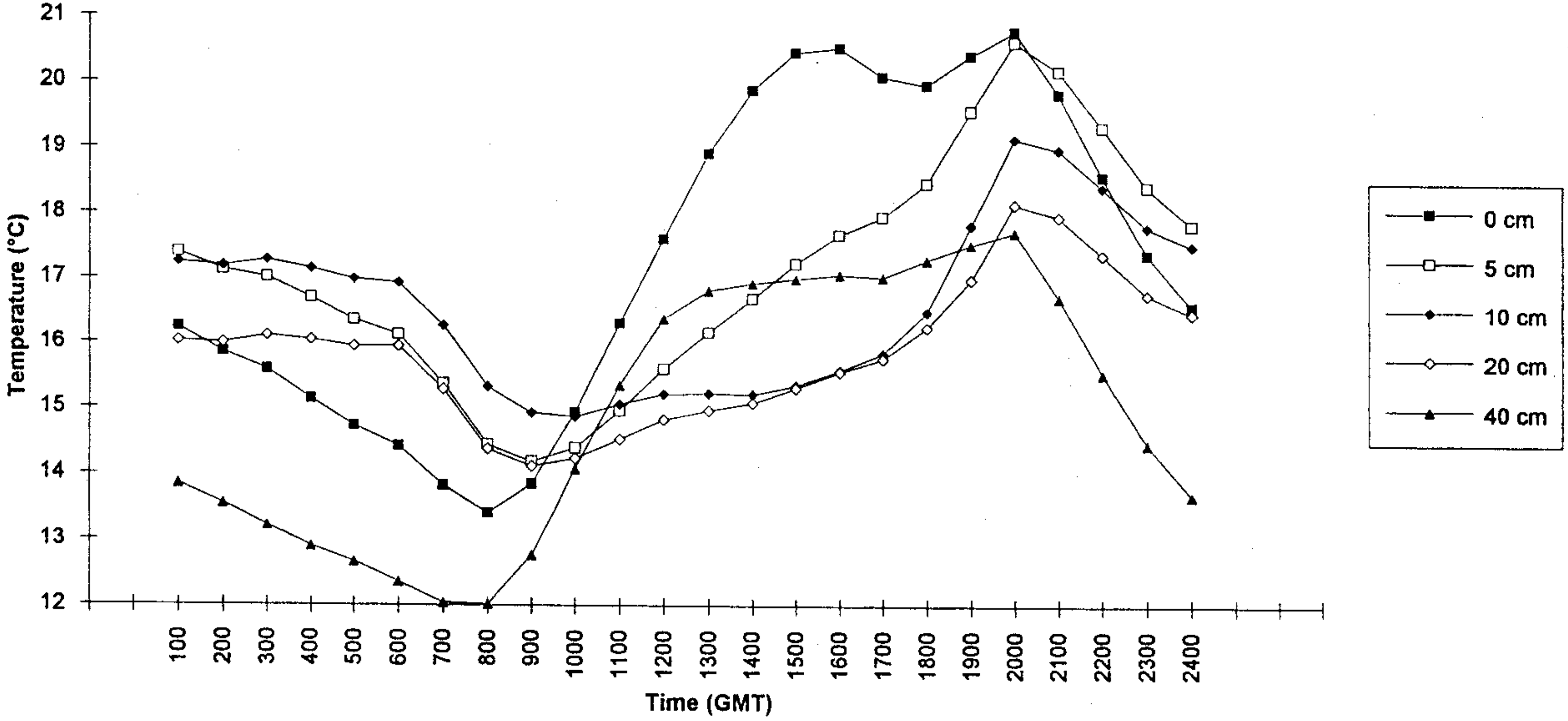
APPENDIX 4

a) Evolution of soil temperature in pool type
b) Evolution of soil temperature in lawn type
c) Evolution of soil temperature in hummock

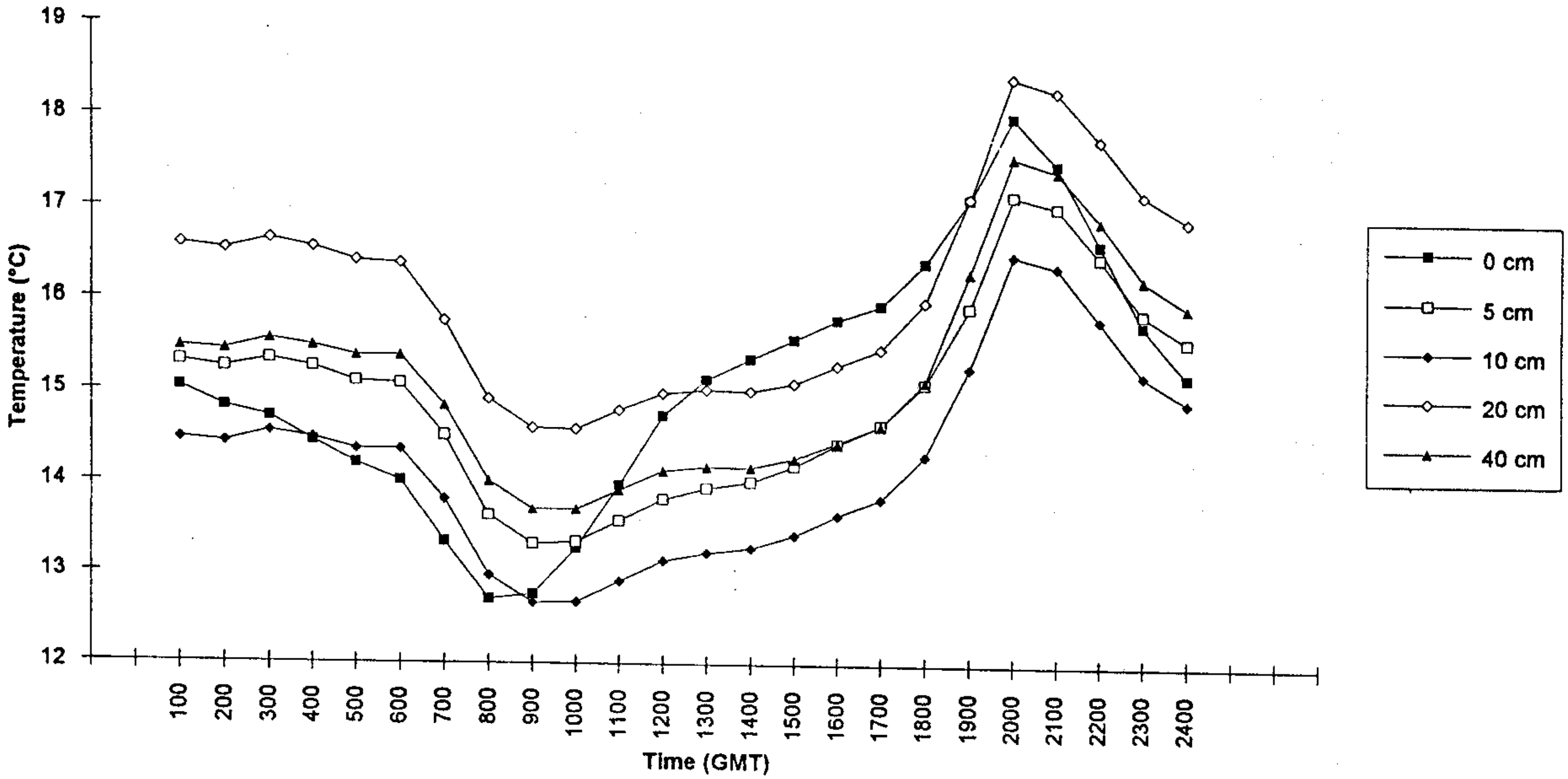
EVOLUTION OF SOIL TEMPERATURE IN POOL TYPE



EVOLUTION OF SOIL TEMPERATURE IN LAWN TYPE



EVOLUTION OF SOIL TEMPERATURE IN HUMMOCK TYPE



APPENDIX 5

a) Table of pool data
b) Table of lawn data
c) Table of hummock data
d)Table of data from core 24 and 26

POOL

julian date	core	flux	temperature	surface	5cm depth	10cm depth	15cm depth
151	14	0.1475		15.12	13.59	14.34	12.66
	13	0.7956		15.16	13.27	14.75	12.76
	18	0.2617		15.6	13.94	15.31	13.17
	24	0.5657		14.6	14.46	15.34	13.08
	29	0.7926		14.3	14.18	14.9	12.85
	32	0.4667		14.99	13.94	14.59	12.57
	23	0.2798		15.53	13.58	14.45	12.38
152	33	0.4482		12.34	13.52	13.62	13.09
	28	0.6064		11.66	12.99	12.77	12.78
	23	0.4976		11.9	12.75	12.66	12.6
153	13	1.4363		9.9	10.14	9.94	10.58
	18	0.0165		9.83	10.13	9.93	10.57
	14	0.1969		9.65	10.13	9.93	10.6
	18	0.3784		9.71	10.11	9.9	10.57
154	24	0.204		14.45	10.76	11.73	10.11
	29	0.823		14.1	11.93	13.17	10.98
155	33	0.0847		15.86	14.06	15.15	12.59
	32	0.3102		16.01	14.46	15.4	12.92
	29	0.2019		15.66	14.52	15.36	12.99
	28	0.1836		15.61	14.55	15.43	13.05
158	13	1.116		19.22	16.15	17.79	14.23
	14	0.1945		18.34	16.4	18.08	14.68
	32	1.057		19.16	16.52	18.23	14.69
	33	0.569		18.69	16.64	18.31	14.87
	32	1.1123		19.23	16.66	18.32	14.81
159	28	0.6922		21.33	16.87	18.8	15.05
	29	1.0078		23.34	17.73	19.38	15.51
	33	0.8128		24.03	18.56	20.79	15.92
	24	0.6438		23.49	19.01	21.2	16.36
	18	0.685		25.6	19.56	21.76	17.42
	23	1.0613		24.11	19.71	22.05	17.71
160	32	1.0286		23.85	18.44	20.57	16.45
	14	0.3613		26.18	19.22	21.63	16.68
	18	1.0189		23.83	21.62	23.41	18.89
166	24	0.362		14.03	11.76	12.48	11.18

mean	0.583423
max	1.4363
min	0.0847
std dev	0.363688

LAWN

julian date	core	flux	temperature	surface	5cm depth	10cm depth	15cm depth
151	12	**0.0423**		14.25	14.22	14.9	13.41
	11	**0.26**		15.48	14.3	15.17	13.5
	10	**0.1509**		13.81	13.96	14.72	13.26
152	22	**0.3439**		17.22	11.99	13.41	13.09
	21	**0.0207**		17.02	12.63	13.64	12.76
	16	**0.1937**		19.29	12.48	13.63	13.07
	25	**0.5278**		12.88	12.69	12.86	12.55
	30	**1.028**		12.76	12.66	12.82	12.53
	30	**0.8827**		12.49	12.49	12.59	12.39
	31	**0.2071**		12.45	12.45	12.54	12.34
153	34	**0.2055**		9.35	10.27	9.92	10.51
	27	**0.2299**		9.25	10.2	9.79	10.47
	21	**0.0408**		9.22	10.2	9.77	10.46
154	30	**0.4496**		11.74	9.76	10.16	9.73
	31	**0.9307**		12.37	10.01	10.45	9.82
	25	**0.2927**		12.44	10.07	10.58	9.86
155	11	**0.1917**		14.26	11.7	12.54	11.02
	10	**0.4768**		15.05	12.03	13.08	11.25
	35	**0.1226**		15.33	12.26	13.36	11.45
	31	**0.2807**		15.49	12.42	13.56	11.52
	21	**0.4138**		16.39	13.68	15.11	12.45
	27	**0.065**		16.77	13.57	15.01	12.34
158	11	**0.2248**		15.22	13.36	13.94	13.17
	12	**0.1178**		15.33	13.35	14.18	13.32
	22	**0.533**		16.1	13.68	14.53	13.41
	25	**0.2694**		16.81	13.83	15.06	13.59
	34	**0.6997**		19.31	17.15	18.24	15.16
159	30	**0.7431**		23.21	18.69	21.38	16.44
	35	**0.5091**		23.16	18.86	21.53	16.61
	16	**1.0516**		22.55	18.95	21.16	16.68
160	10	**0.9156**		25.29	19.67	23.18	17.29
	12	**0.551**		25.78	19.94	22.91	16.96

mean	0.405375
min	0.0408
max	1.0516
std dev	0.305921

HUMMOCK

Julian date	core	**flux**	temperature surface	5cm depth	10cm depth	15cm depth
	5	**0.1156**	15.11	12.37	14	11.56
	1	**0.331**	15.84	12.47	14.43	11.44
151	7	**0.1727**	14.82	12.69	13.98	11.79
	2	**-0.0274**	15.16	11.57	12.95	10.77
	3	**0.0375**	14.54	11.93	13.22	11.21
152	19	**0.1323**	14.12	12.03	13.26	11.4
	20	**0.144**	13.24	12.15	13.2	11.55
	7	**0.2436**	9.46	9.98	9.93	10.51
	5	**-0.0548**	9.56	9.96	9.9	10.46
153	26	**0.0479**	9.49	10	9.95	10.49
	2	**0.0127**	9.16	10.25	9.78	10.52
	3	**0.0604**	9.18	10.28	9.81	10.53
	7	**0.0218**	9.16	10.29	9.83	10.55
	26	**0.0517**	12.23	10.13	10.8	9.98
	19	**0.0419**	12.56	10.2	10.97	9.99
154	20	**0.0925**	12.65	10.27	11.08	9.99
	15	**0.376**	12.99	10.26	11.11	9.97
	26	**0.0705**	14.79	11.98	13.51	11.1
	15	**0.0937**	15.17	11.96	13.6	11.13
155	19	**-0.0033**	14.82	12	13.57	11.18
	15	**0.4139**	17.47	13.41	14.66	12.81
	7	**0.1206**	17.45	13.61	14.74	12.55
158	2	**-0.0116**	17.74	13.67	14.88	12.66
	5	**0.1385**	17.44	13.89	15.26	12.78
	1	**0.0712**	21.36	14.22	16.56	13.25
	3	**0.0454**	22.61	13.99	16.51	12.88
159	2	**0.0598**	21.71	14.88	17.43	13.72
	1	**0.00248**	23.46	15.66	17.7	14.12
	20	**0.238**	23.14	15.92	18.24	14.32
166	26	**0.1413**	15.01	11.77	12.74	11.16

mean	0.105996
min	-0.0548
max	0.4139
std dev	4.265318

Methane emissions versus drop in water level in pool 24

	Methane flux (µg/m/s)	
	Temperature (°C)	
Drop in water level	*morning*	*afternoon*
(cm below surface)		
2cm	0.461	0.7853
3cm	0.4715	0.7125
4cm	0.0237	0.0367

Methane emissions versus increase in water level in hummock 26

	Methane flux (µg/m/s)	
	Temperature (°C)	
Drop in water level	*morning*	*afternoon*
(cm below surface)		
9cm	0.228	0.3946
3cm	0.2618	0.3323
3cm	0.0472	0.0386