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CAN CLIMATE CHANGE TRIGGER NON-LINEAR AND TIME-DELAYED RESPONSES TO POLLUTANTS STORED IN SOILS, SEDIMENTS AND GROUND WATER?

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Abstract

Climate change is just part, though increasingly dominant, of global environmental change. Climate change acts upon an already pre-stressed and polluted world. It aggravates in a sometimes unexpected way ecotoxicological stresses on flora, fauna, ecosystems and natural resources by releasing stored pollutants. The project "Chemical Time Bombs in Europe" by IIASA and the Foundation for Ecodevelopment takes climate change in account as a major trigger mechanism. "Predicting the unpredictable" (Stigliani et al., 1991) is the name of the game.

1. Exposure of polluted soil, sediment and groundwater to changes in environmental conditions ("chemical time bombs")

Man-induced chemical contaminants have been accumulating in soils and sediments for the last two thousand years. An early example is the pollution caused by mining. Since the early Industrial Revolution, two centuries ago, the scale and pace of environmental contamination by industrial, commercial, agricultural and domestic activities have steadily increased. The pattern of pollution is characterized not only by local, highly concentrated sites such as toxic waste dumps and mine tailings, but also by lower concentrated pollution dispersed over large areas such as copper additives

in fodder which is spread with manure over pasture lands, pesticides dressed over croplands and forests, and the toxic mix of urban run-off leaking into rivers, lakes and estuaries (Stigliani 1988; Stigliani & Salomons 1990).

Soils and sediments can store and immobilize substances as if in "chemical sinks" and thus the ecotoxicological consequences may not be immediately manifested and hence not studied. Normally in ecotoxicological risk assessments the no-effect-concentration (NEC) of a chemical to a standardized group of test organisms is compared with the predicted environmental concentration (PEC) of that chemical at realistic potential emission concentrations. If the PEC is greater than the NEC the system is said to be at risk (fig. 1). The PEC/NEC ratio,

however, ignores the fraction entering into the environment that is not bio-available to the organisms, either by bonding to particles of sediment and soil that are not swallowed immediately by the test organisms, or non-available by leaking directly into the deeper ground water. PEC/NEC ratios are thus based on assessments of acute toxicity or subchronic tests of some weeks to a few months at the most, but not on potential responses after some decades. Straight-forward ecotoxicology does not (yet) take chemical time bombs in account (Hekstra 1991b).

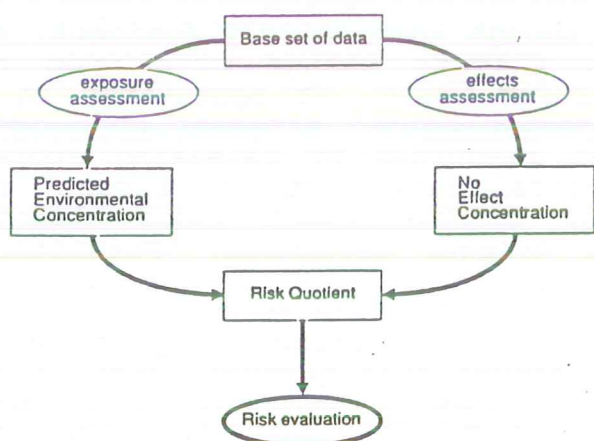


Figure 1. Basic procedure of ecotoxicological risk assessment. Notice that only the biologically available fraction of the chemical is taken into consideration. Immobilized fractions adsorbed to particles of soil and sediment or leached into the deeper ground water induce no direct toxic effects but they may get mobilized much later due to climatic and land-use changes.

The natural or technical processes of sequestering of chemicals in soils, sediments and ground water do not guarantee, however, that the chemicals are safely stored forever. Environmental factors influencing the storage capacity and the later

bio-availability to organisms, can change and indirectly cause sudden, often unexpected mobilization of chemicals in the environment. Among these "triggering" environmental factors that change storage in the soils and sediments and bio-availability to organisms are acidification, eutrophication, erosion, flooding, drought, and other symptoms of landuse change and climate change. Forest dieback in the early 1980s, which was caused at least in part by soil acidification and air pollution, is a recent example of a sudden, unanticipated problem resulting from certain delayed responses to chemical pollutants stored for long in the forest soil (Stigliani et al. 1991).

Although local governments now seem to have learned the hard way not to build residential areas over former waste dumps, mainstream regional economic and landuse planning is generally overlooking the problems caused by the legacy of chemicals accumulated in the environment over time. In advanced countries (hopefully in all) soils and sediments should no longer be considered receptacles for storing and eliminating pollutants for eternity.

By definition (Stigliani et al. 1991), "a chemical time bomb is a concept that refers to a chain of events resulting in the delayed and sudden occurrence of harmful effects caused by the mobilization of chemicals stored in soils and sediments in response to slow alterations in the environment".

Four remarks derive from this definition. Firstly: only when the buffering capacity of an ecosystem is too small to retain or counteract chemical inputs will harmful effects become apparent. Secondly: in

contrast to conventional types of pollution, CTB's involve a time delay between the accumulation and the adverse effects and their appearance may be quite unexpected. Thirdly: CTB adverse effects express themselves suddenly, relative to the time of accumulation. Finally the effects are discontinuous and non-linear. Once the soil vulnerability has passed a threshold the system changes behaviour, i.e. from a sink for the chemical into a source which releases chemicals.

The environmental "surprise" of a CTB will occur when changes in known critical conditions go unnoticed, or when relationships governing non-linear interactions between the chemical activity and the changing conditions have not been scientifically established, e.g. the vulnerability of a soil to be harmed in one or more of its ecological functions is not studied. Strong and delayed responses (e.g. upon erosion or acidification) may be observed in soils that have accumulated large amounts of mobilizable chemical compounds within the soil-plant-fauna system. The severity of the impact depends on the physical degree of vulnerability (e.g. slow soil creep versus landslide) and the type of trigger (e.g. gradual change in soil moisture versus flooding by a hurricane). Weak and more rapid responses ("whimpers" rather than "explosions") may be observed in soil systems from which chemical compounds are easily lost with run-off or leached into the groundwater. Here in this instance is no specific "trigger" but a "leak" as if a sponge gets saturated.

What matters in both types, CTB explosions and whimpers, is:

- a. the actual degree of chemical loading of the system in extent and depth,

- b. the key geochemical, soil structure and groundwater parameters (calcium content, weatherable silicates, texture and aeration, soil depth and horizons, clay mineralogy, iron and aluminium (hydr)oxides, pH, organic matter type and content, drainage and percolation, redox condition, water table, direction and rate of flow),
- c. the occurrence and type of leaking or bleeding of the polluted system, and
- d. the release or trigger mechanisms.

Apart from digging, ploughing and draining for agricultural, urban-industrial and infrastructural purposes, most of the CTB trigger mechanisms are related to climate change: moisture regime, flooding, erosion, salinization, aeration, seepage and (often indirectly over microbial processes) organic matter content and nitrification. How climate change can affect the mobility of stored pollutants in soils, sediments and groundwater is shown in figure 2.

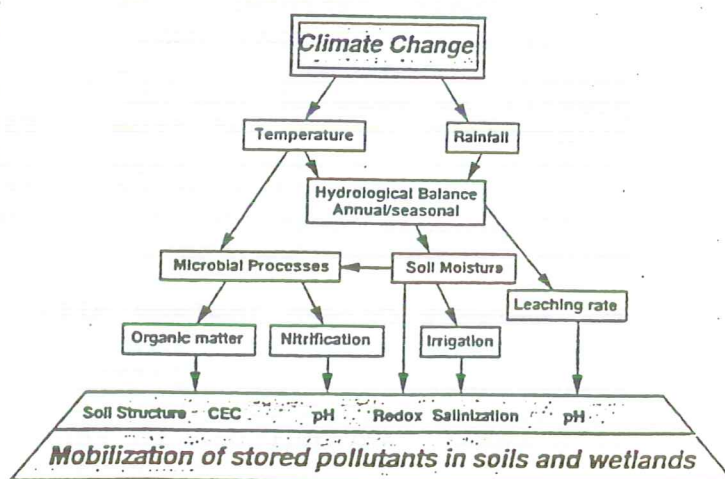


Figure 2. Pathways how climate change through intermediate processes can influence the mobilization of stored pollutants in soils and sediments (Stigliani & Salomons 1990).

2. Climate change, soil moisture and redoxpotential

The overall picture that emerges from the GISS temperature and rainfall scenarios and the Variable Cloud Soil Moisture model of Manabe and Wetherald (1987) for a doubling of atmospheric carbon dioxide equivalent (figures 3 and 4; Hekstra 1987) is as follows. Northern Europe would experience 5-9 °C warmer winters with increased soil wetness and only 2-3 °C warmer summers with increased drying-out of soils.

Southwestern Europe in winter and in summer would be 3-5 °C warmer with slight increase in soil moisture in winter and a significant drying-out in summer. Southeastern Europe and the adjacent Middle East would be 4-5 °C warmer without increased soil moisture in winter and 3-4 °C warmer with a significant drying-out in summer. Other, more central parts of Europe would be intermediate between these extremes. The result would be that semi-desert conditions would prevail in most of the Mediterranean region and from Hungary to the Lower Volga and that semihumid steppes would prevail over the Benelux and German Lowlands.

The present German lowland climate would move far into the Fennoscandian lake districts and render them much dryer than at present. Agriculture in Fennoscandia and northern Russia will expand on previous podzols with almost no buffering capacity and thus requiring very heavy liming. The deep black soils of Russia and the Ukraine and the forest grey soils of central Europe will rapidly

oxidize and over a wide extent disappear, thus releasing most of the pollutants that they contain into surface and ground waters. (fig. 5; Hekstra 1991a).

As a result, most European soils will be much longer dry to extremely dry, although episodes of more intensive winter rains may occur. If the soil is not mechanically compacted due

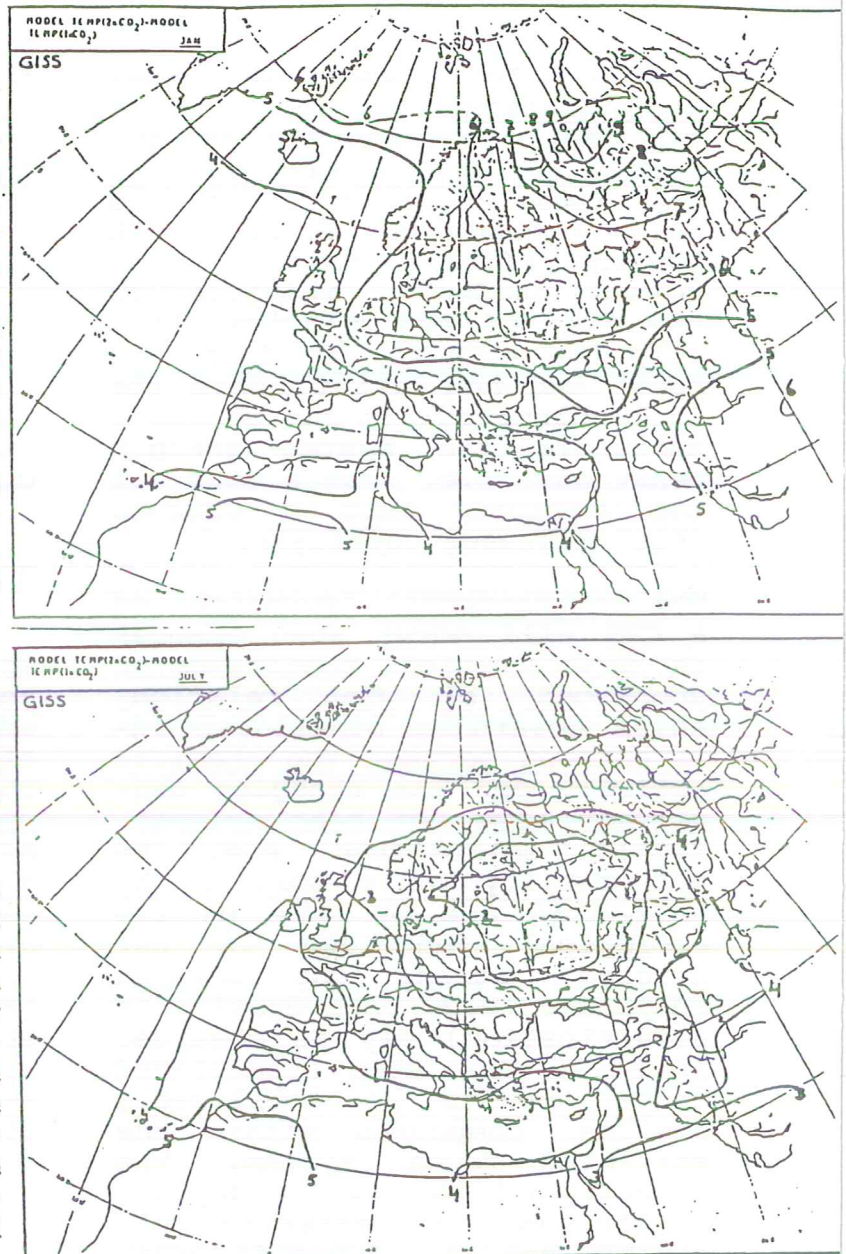


Figure 3. GISS Model changes in temperature at CO₂ doubling equivalent in January (a) and July (b). (Hekstra 1987).

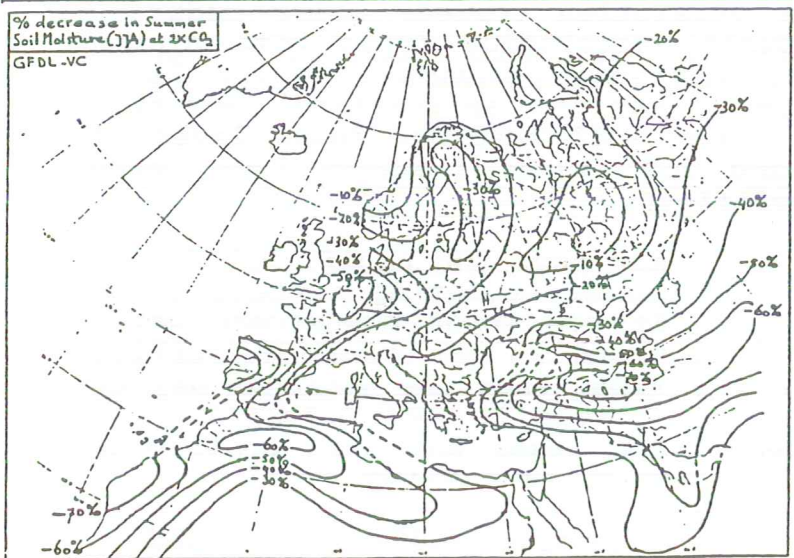
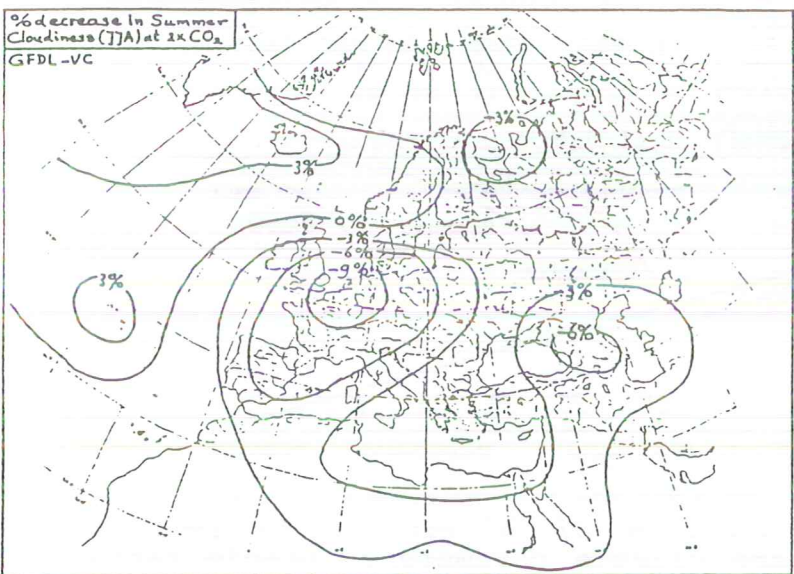
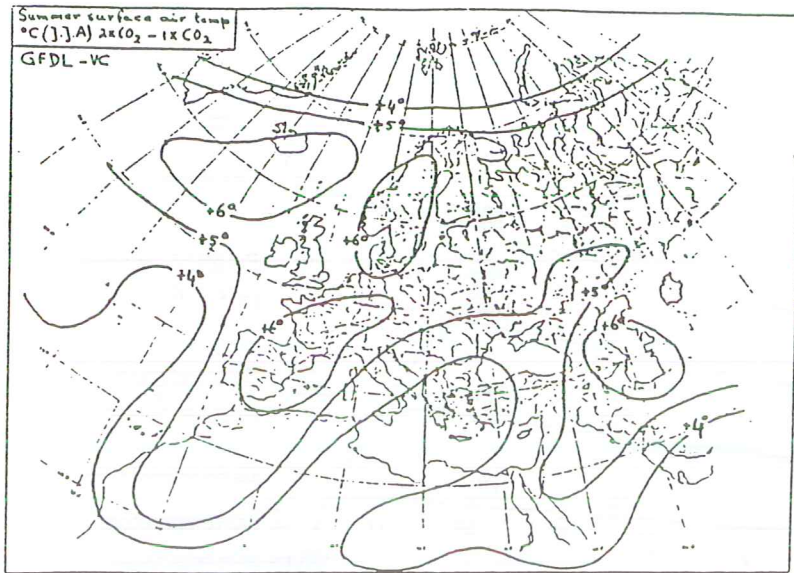


Figure 4. GFDL-VC Model changes in summer surface temperatures (June-Aug)(a) percent decrease in summer cloudiness (b) and percent decrease in summer soil moisture (c)(Hekstra 1987).

to agricultural and infra-structural/ technical uses, air will penetrate much deeper, and in conjunction with higher temperature, will stimulate microbial decomposition of organic/humic matter and in this way reduce the water and mineral holding capacities. The deep anaerobic (reduced) soils become aerobic (oxidized). Not only is there a multi-annual trend towards dryer soils, but also is the annual amplitude in the so-called redox potential becoming much greater: anaerobic under flooded conditions and aerobic under drought conditions.

As is illustrated in figure 6 (Stigliani 1988), moist soils and wetlands function as sinks for sulfates, nitrates and toxic substances. Under anaerobic conditions sulfate is reduced to immobile sulfides. The degree of sulfur storage depends on hydrological conditions and residence times of the sulfate, but it can be substantial, up to two-thirds of the inputs. By this mechanism, wetlands contribute substantially to decreasing the sulfate concentrations passing through them. Alternatively, during hot dry periods wetlands may become a source of sulfates and of the metals that go with them. They may subsequently be flushed during heavy rains to downstream waters.

Wet soils also function as a nitrate trap. The nitrogen products that result from microbial action are not stored but vented out in the atmosphere as N_2 or N_2O . In certain situations where nitrate is a pollution problem, the wet soil

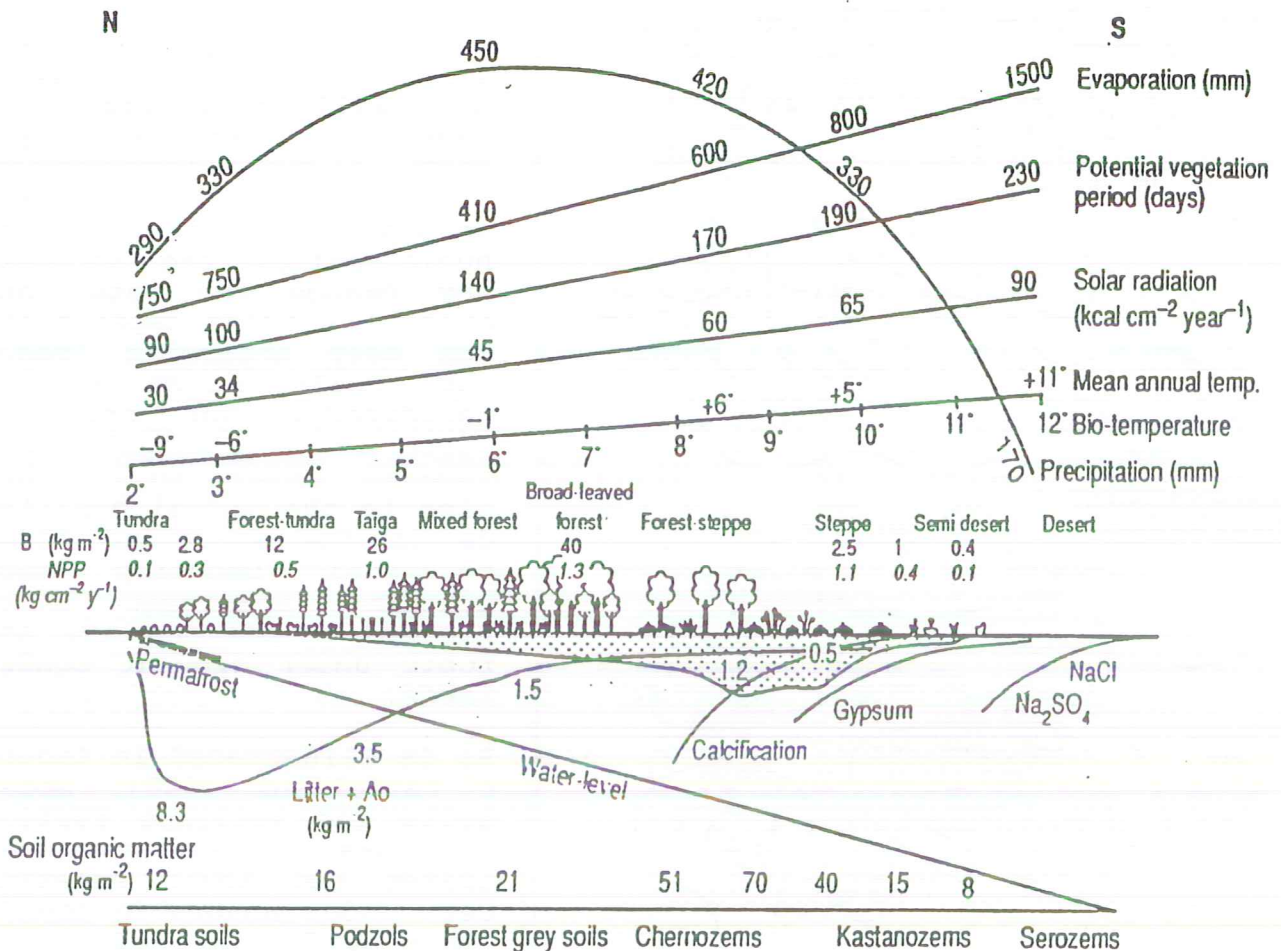


Figure 5. North-to-south succession of biomes in Europe from tundra to desert. Indicated are climate parameters (precipitation evapotranspiration, potential vegetation period, solar radiation mean annual and bio-temperature), vegetation types with biomass and net primary productivity, and soil parameters (water level, permafrost, calcification, gypsification, salinization/ sodification, litter accumulation in upper soil horizon, humus layer (in gray), soil organic matter and soil types (Hekstra 1991, after Schennikov, in Walter 1970; modified).

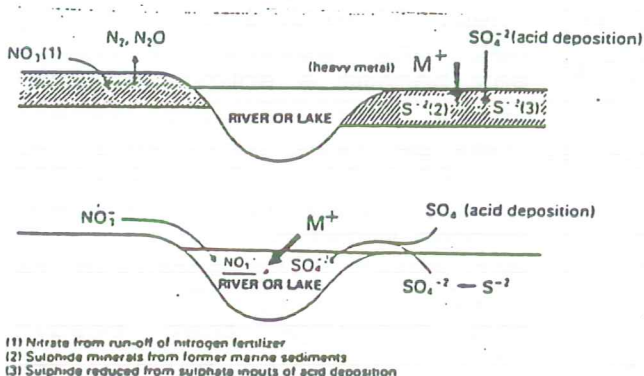


Figure 6. Wetlands as sinks and dry lands as sources for nutrients and micropollutants (Stigliani 1988).

may have the beneficial function of depleting nitrate before it can enter downstream waters where it can cause eutrophication. When the wetlands dry out nitrate is enhanced into rivers and lakes and thus contributes to water fouling.

Anaerobic soils also tend to accumulate (heavy) metals mostly as precipitated sulfates and insoluble salts, but these may get mobilized when the soils dry out. Chlorinated hydrocarbons such as PCBs, furanes and dioxins and persistent pesti-

de residues such as of paraquat/diquat, react differently to changes in redox potential. If PCB- or dioxin-containing sludge is kept strictly anaerobic for many years (decades) a gradual de-chlorinization of most (but not all) fractions will take place, whereas aerobic conditions (oxidation) will enhance leaching of these chemicals from sludges. Paraquat and diquat are potent herbicides as long as being on the plant, but these non-chlorinated substances are quickly inactivated when on the soil by strong bonding to humic (organic) particles and are even much stronger bonding to clay particles (IPCS 1984). This bonding potential can repress bonding of other pollutants and hence enhance their mobilization, particularly when the total of bonding sites is getting reduced due to climatic change (Stigliani & Salomons 1990).

3. Climate change, salinization and cation exchange capacity

Soil moisture, being the result of rainfall, evapotranspiration and waterholding capacity of the soil organic matter, influences soil salinity as well. Moreover, if soils were to dry-out over large areas, farmers tend to resort to increased reliance on sprinkling or even irrigation, and hence more rapid decline of groundwater tables and increased salinity of surface waters may take place.

Over ever larger areas of Europe surface and ground waters are getting increasingly more saline (fig. 7; Szabolcs 1991). If regionally or locally irrigation raises the water table of salty ground water to a critical depth of about two meters below the surface, the upward movement is enhanced through

capillarity and subsequent evapotranspiration, thus leaving a salt crust on the surface of the soil. The deeper salty water can also be drawn nearer to the surface by increased extraction of the overlaying fresh water for drinking water production and industrial water extraction.

In any case where the salt concentration is increasing in a soil or sediment in which large amounts of pollutants have already accumulated, the latter will be set free, due to a physical replacement process named cation exchange capacity. Such may also happen particularly in estuaries of large rivers with polluted sediments. If the sediment was deposited under fresh water conditions and gets increasingly exposed to sea water because of sea level rise it will start to release in particular the contained heavy metals. Furthermore, increased storminess may perturb the sediment and remobilize the heavy metals in it (fig. 8).

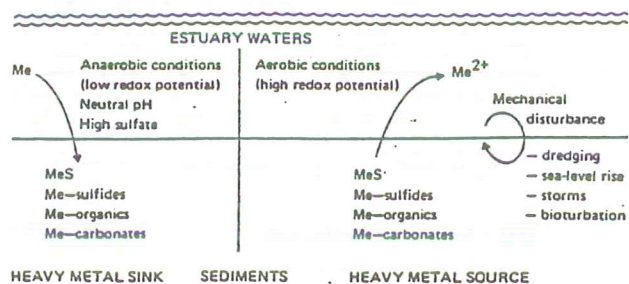


Figure 8. Estuarine sediments as a sink and a source of heavy metals and micropollutants (Stigliani 1988).

Organic matter generally enhances the number of exchangeable cation sites in soils. Hence any reduction in organic carbon content by climate-induced oxidation could substantially decrease the CEC and set free heavy metals and organic micropollutants in a more bio-available, that is more toxic form.

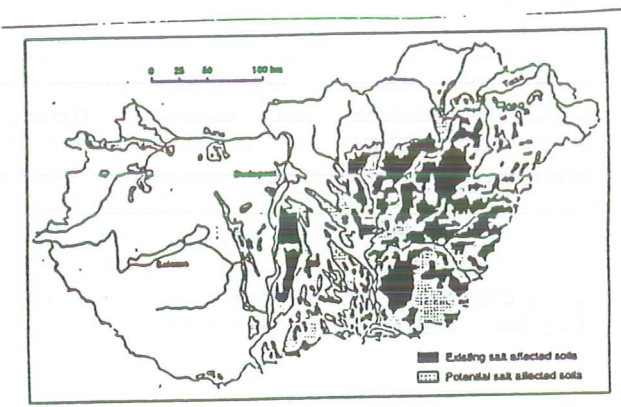
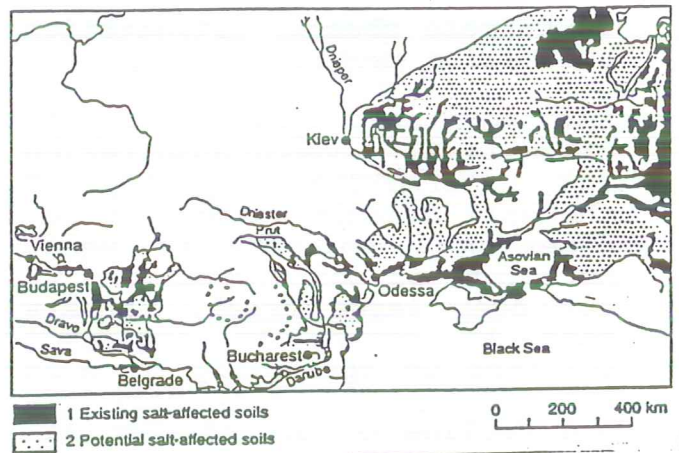
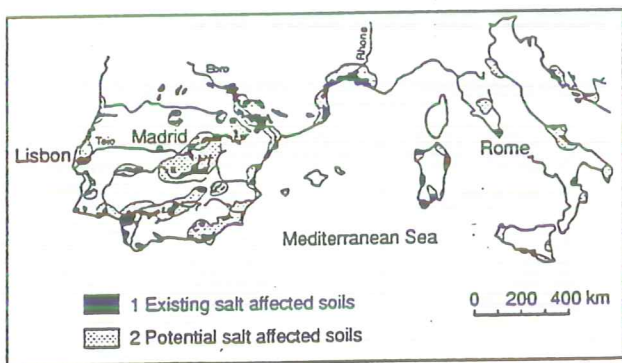
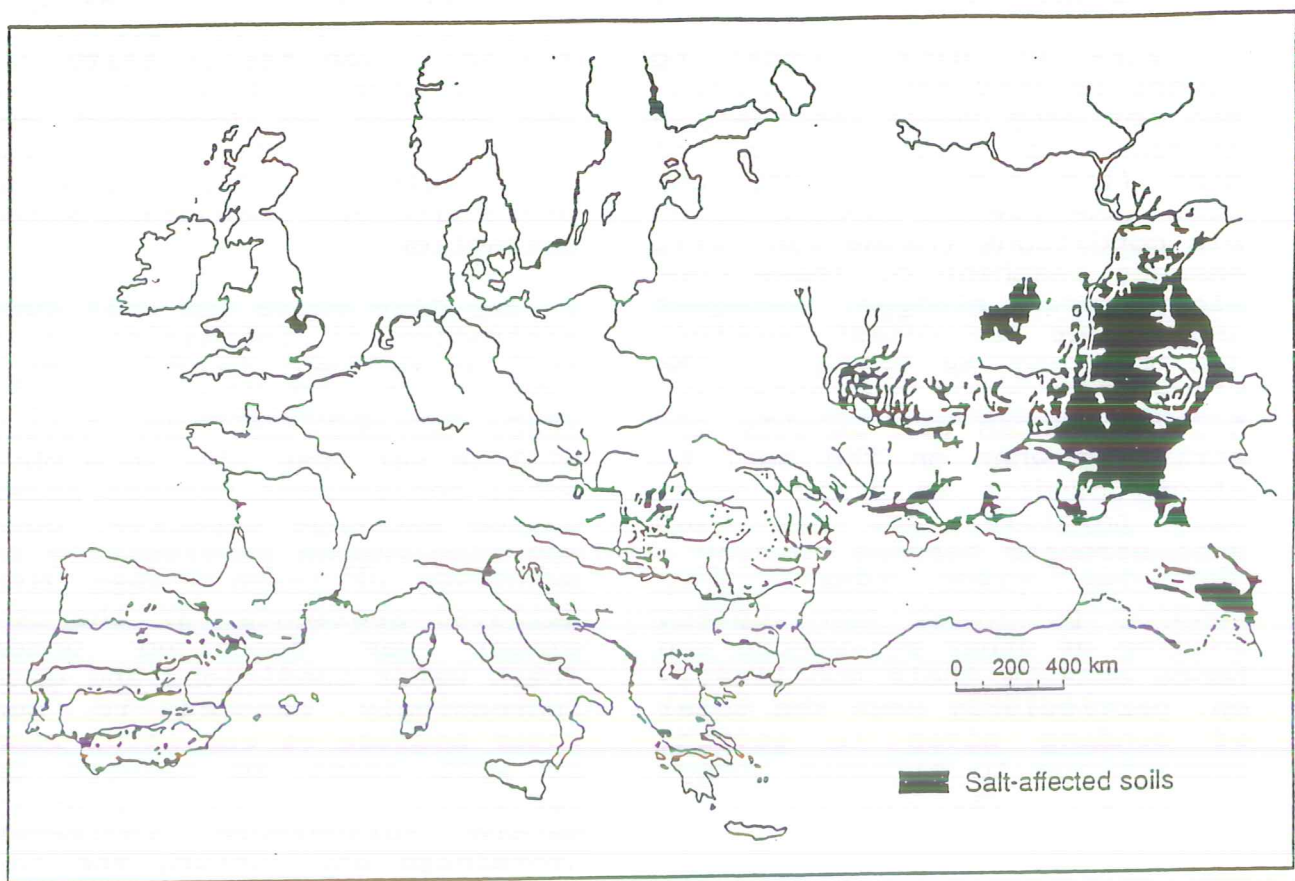


Figure 7. Present and potential salt-affected soils under presumed climate warming at doubling atmospheric Carbon dioxide content (Szabolcs 1988).

4. Climate change and alkalini- zation/acidification

When evapotranspiration is greater than precipitation, there is no net removal of cations through downward leaching, and alkaline cations will accumulate in the soil when the weathering of lime stone and Karstic rock such as in southern Europe generates base cations like Ca^{2+} , Mg^{2+} , Na^+ and K^+ . If the weatherable parent material is not alkaline but granitic or peaty acid H^+ -ions will accumulate and render the soil acidic. Under a regime of surplus rainfall, however, even alkaline cations will leak out and get replaced by H^+ -ions from rain water and the soils will get less alkaline. Heavy rainfall on already strongly acidic soils will render them less acidic. More extreme seasonal fluctuation in rainfall due to climate change will strongly affect the mobilization of pollutants in soils and sediments. If dryer summers are followed by wetter winters and if the acid buffering capacity of the parent material is exhausted a small change in soil pH can cause a huge uptake of heavy metals, especially of cadmium, by plant roots. The percent of heavy metal cation adsorbed to soil components undergoes an abrupt change over a narrow pH range (fig. 9).

Experiments have demonstrated the effectiveness of decreasing the bio-availability of cadmium by the acidity of agricultural soils by liming. Now that liming is getting less practiced (in the west due to land set-aside policies because of over-production; in the east because farmers can no longer afford the costs of liming) most of Europe will witness enhanced mobilization of cadmium from polluted land. The bio-availability of cadmium and lead to

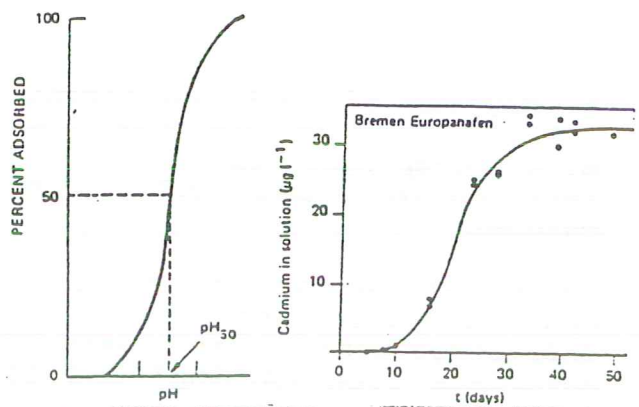


Figure 9. (a) Typical pH adsorption curve for divalent cations on hydrous metal oxides showing that a shift of one pH point may change adsorption from 90 to 10 percent and vice versa. (b) Remobilization of cadmium upon exposing harbor sludge from the Europahafen Bremen to sea water 32 promille and pH 7.9 (Stigliani 1988).

worms in relation to the acidity of the soil is shown in fig. 10. If soil pH shifts from 6 (close to neutral) to 3.5 (very acidic) the take-up of cadmium by the worms is doubled and of lead is more than quadrupled. When the polluted worms are eaten Pb and Cd accumulate in the food chain.

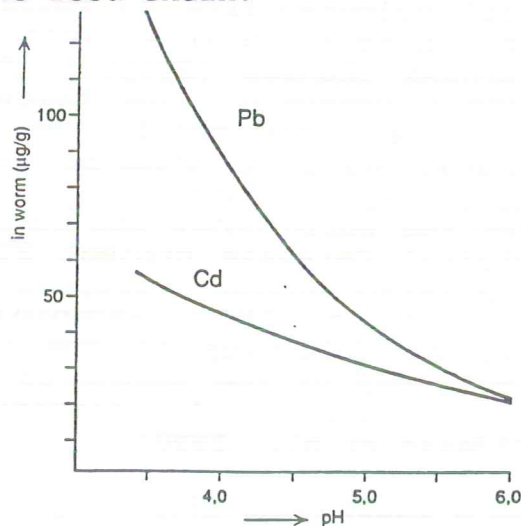


Figure 10. Lead and cadmium in earth worm near metal industry at Budel, Netherlands in relation to soil pH at fixed metal concentrations of 0.8 µg/g for Cd and 85 µg/g for Pb and 10 % organic matter (Van Straalen and Bergema 1990).

5. Mapping of soil and terrain vulnerability to specified chemical compounds in Europe in relation to climate and landuse changes

Soils can be used to build on and in (urban-industrial and infrastructural), to extract materials from (mining) and to deposit materials on or in. Apart from these socio-technical functions, relevant ecological functions of soils are:

- production of biomass,
- genetic reserve for biota,
- protection against exogenous changes, notably by
 - * filtering
 - * storage
 - * buffering and
 - * transformation of substances.

As Europe is increasingly integrating its socio-economic and physical-infrastructure planning (European Economic Community: European Energy Charter), an appropriate common geographical information system should include also the mapping of soil vulnerability to pollution, in relation to climate and landuse changes (Batjes, 1991; SOVEUR workshop). The relevant parameters can readily be accommodated in a database management system such as developed for the World Soils and Terrain Digital Database project SOTER (UNEP-FAO-UNESCO cooperative project at ISRIC, Wageningen, NL, as follow-up to the UNEP World map of the status of human-induced soil degradation; Oldeman et al., 1990).

As a basis, the FAO/UNESCO soil map of Europe (1:5M scale) can be taken, but aggregation of additional national soil maps at scales of 1:1 or 1:2M and single value thematic maps for key parameters such as CaCO_3 content, weatherable silicates, soil depth, clay, iron and aluminium (hydr)oxide and organic

matter content, water table and directions of groundwater flows etc. is important. Subsequently cartographic "windows" of higher resolution should be made in critical areas. One thematic map could display the predictable salt and brackish water penetration in the coastal lowlands (more than half of the Netherlands and much of northwestern Germany; fig. 11) where much of the arable land contains heavy metals and pesticides and where municipal and industrial waste dumps will get increasingly exposed from underneath to the penetration of brackish water.

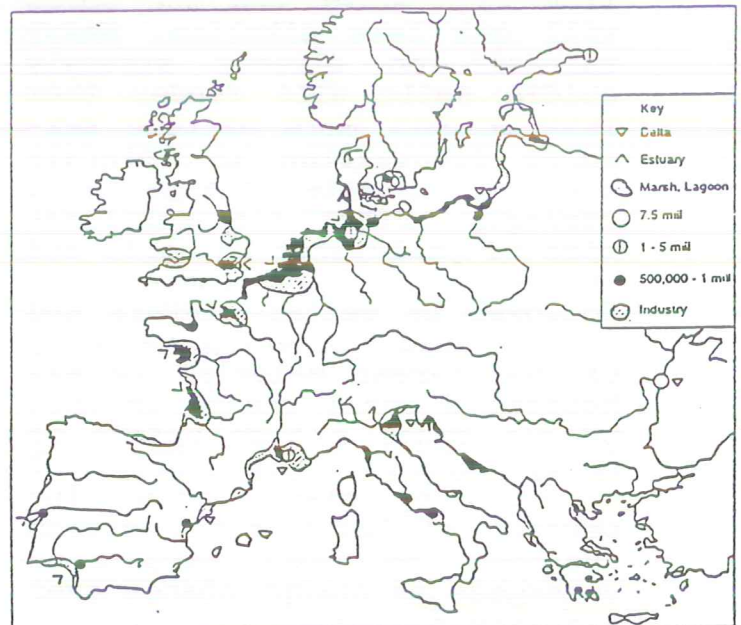


Figure 11. Vulnerability of coastal zones in Europe to sea level rise and brackish water infiltration in lowland rivers and ground water. Although a sea level rise of five meter in itself is not likely to happen in several centuries, the five meter elevation line indicates the zone where problems with brackish water infiltration in rivers and groundwater and capillary uplift to the surface is quite possible within several decades (Jelgersma 1987).

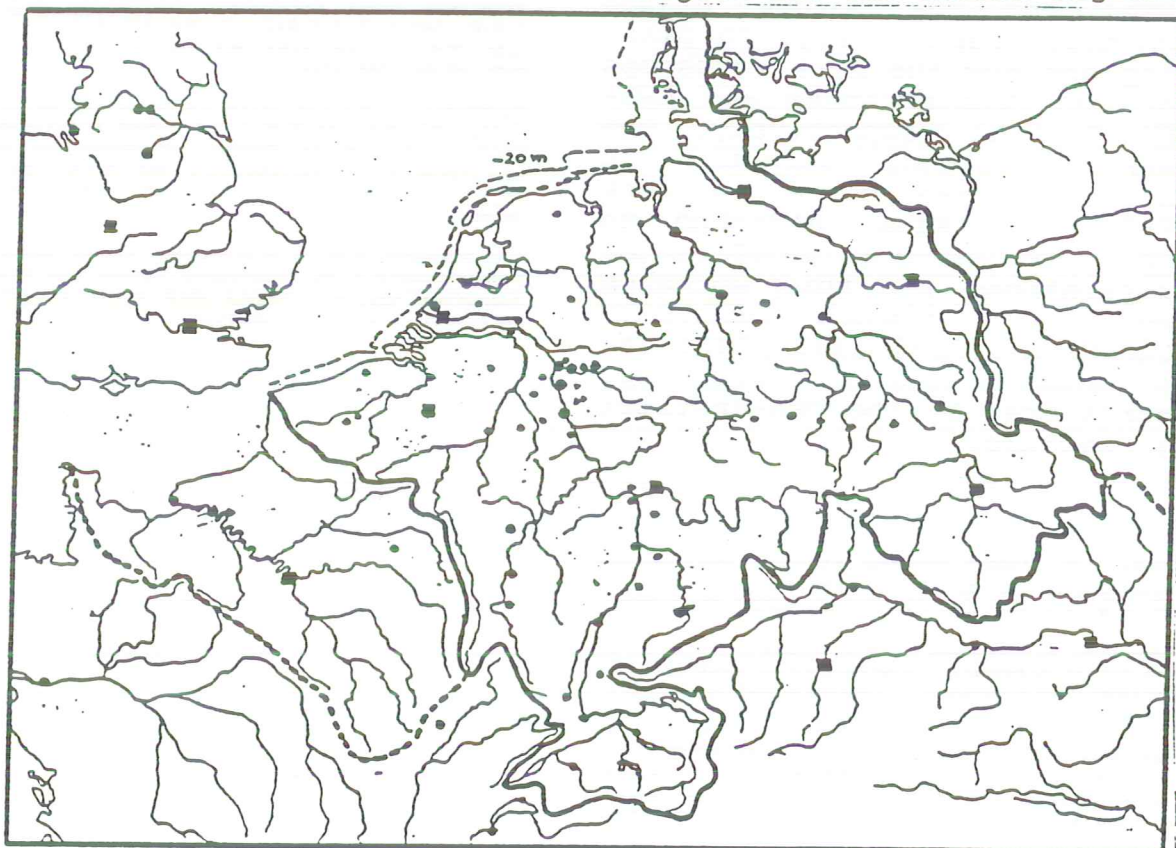
Vulnerability of soils to "diffuse" acidification by air pollution is relatively well studied in the IIASA RAINS Model. Mapping can be considered at a 1:5M or 1:1M scale. Localized CTBs, such as landfills and mine spoils, which are wide spread in Europe and can cause severe environmental and socio-economic problems in view of climate change and sealevel rise, can only be mapped meaningfully at larger "windows". Windows can also be used for mapping environmental risk of e.g. diffuse pesticide contamination at a specific site in relation to meteorologic conditions (Blüme and Brümmer 1987). Although many technical and organizational matters remain to be resolved, the SOVEUR workshop proposal for an all-European mapping of soil and terrain vulnerability to specified chemical compounds is worth exploring. As at present no generally accepted procedure is yet available for the mapping

of ecodistricts and ecoregions, additional effort is needed to refine this approach (Klijn, 1991). A start could be made for the northwestern Europe including the Benelux, France and Germany.

6. Climate Change and Chemical Time Bombs in the Northwest European EWERMS Region

From Esbjerg to Calais several river system catchment areas empty into the Wadden Sea and southern North Sea, which is a huge and coherent delta, receiving the silts, sediments and pollutants from all land north of the central European watershed. Geographically, ecologically and socio-economically the region is so coherent that it deserves the name EWERMS Region, after the initials of the rivers Elbe, Weser, Ems, Rhine, Maas and Schelde.

Figure 12. The EWERMS Region.



Within the CTB project are activities to increase scientific understanding of the problems (e.g. the soil-chemical-climate-acidification relationships) and workshops to increase regional awareness and basinwide research cooperation. Thematic (conceptual) workshops were held on CTB definition, concepts and examples, soil vulnerability mapping, scenarios of climate and landuse change, CTBs from landfill and mining spoils, while workshops on data collection of chemical loading and on modelling of leaching, triggering and "explosions" are in preparation. Seven basic desk studies were financed by the European Community (DG XI) regarding soil physics, biochemistry, microbial activity, climate interaction and specific examples from different soils and sediments. Regional workshops have so far been held for the Danube Catchment Area (Budapest, Dec.1990), the Baltic Region from Trave to Lake Ladoga (Tuczno, Poland, June 1991) and the Nordic Region (Uppsala, Sept. 1991). In planning are now two more workshops for the Mediterranean and EWERMS Regions respectively. The EWERMS Regional workshop is going to take place in June 1992 at Potsdam, attached to the SETAC-EUROPE conference. Preparations for this workshop and joint research programme (UBA-RIVM-IIASA) take place 16-19 January 1992 at Offenburg, coordinated by the Öko-Institut at Freiburg.

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STUDIES OF THE SPATIAL AND TEMPORAL VARIATION OF SOIL TEMPERATURE AND SOIL HEAT FLUX

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(1) INTRODUCTION

The variation of soil heat flux and temperature needs to be considered in many fields of environmental research. Soil, the surface which intercepts much of the incoming solar radiation, is an important source of heat for the lower atmosphere. Its porous structure provides micro-environments which are insulated from the extremes of heat and cold at the surface and yet are provided with air, water and nutrients; this makes soil a major store of greenhouse gas precursors and an important medium for organisms which produce the gases.

In biology and ecology soil temperature is an important controlling factor for plant development as well as for the activity of soil organisms and chemical processes. Soil heat flux is one of the terms in surface energy balance equations for evaporation from the surface and as such has been widely studied.

This report outlines a wide range of related work on soil heat fluxes and temperature carried out by the Institute of Hydrology. After discussion of the basic theory and definitions, results from research programmes are presented to give examples of geographical variation and more localised effects caused by changes in season and location. The aim of the report is to provide information related to soil heat for a range of situations to be used as a background for further discussions.

(2) BASIC THEORY AND DEFINITIONS

Soil temperature is determined both by the flow of heat upwards from the interior of the Earth as well as the surface conditions. However, the flow of geothermal heat is very small (about 0.04 Wm^{-2}) and for most purposes it may be neglected as the geothermal temperature gradient associated with this flow is only about 0.03°C per metre.

There being no significant sources of heat within the soil, the soil surface is the most important source of variation in soil temperature. Solar radiation reaching the soil surface is partly reflected, the rest being used to heat the soil and the air and to evaporate water. Where vegetation is present the plant surfaces intercept most of the incoming radiation, and the soil receives much of its heat from re-radiation and by conduction from the air. Some of the heat is re-radiated at long wavelengths, according to Stefan's Law, the soil surface behaving as a black body.

When the soil surface is heated energy is transported vertically by conduction to the cooler soil below. At night the thermal gradient near the surface reverses and heat is returned to the surface to be radiated, lost by conduction to the air or used for evaporation from the soil surface. Deeper in the soil the temperature distribution takes the form of a wave which propagates downwards being attenuated rapidly. In addition to the strong diurnal wave, which is most prominent on clear summer days, there is an annual wave which penetrates to a much greater depth.

This report will only discuss in detail the basic simple homogeneous model for soil heat conduction.

The observed variations in soil temperature at a site resemble temperature variations inside a semi-infinite homogeneous conductor subjected to a periodic surface temperature, and this model has been used extensively to describe soil phenomena.

The equation for the one-dimensional conduction of heat in a solid is

$$\rho \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where T is temperature, λ the thermal conductivity of the medium, ρ its density and c its specific heat. The assumption of homogeneity leads to the simplified equation

$$\frac{\lambda}{\rho c} \frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t} \quad (2)$$

The combination $\lambda/\rho c$ is referred to as the thermal diffusivity of the material and is usually denoted by κ . Applying the boundary condition at $z = 0$,

$$T(0,t) = T_o \cos \omega t + T_m \quad (3)$$

a solution of periodic form and angular frequency ω , gives

$$T(z,t) = T_o \exp(-z/D) \cos(\omega t - z/D) + T_m \quad (4)$$

which has the required form of an attenuating wave propagating downwards (i.e. in the direction of z increasing). The distance D , sometimes referred to as the 'damping depth', is given by

$$D = \left(\frac{2\kappa}{\omega} \right)^{1/2} \quad (5)$$

and is the depth in which the wave amplitude is reduced by a factor of e . It is obvious from (5) that low frequency oscillations, such as the annual variation of surface temperature, will penetrate to greater depth than high frequency oscillations such as the diurnal wave. This expression also provides an explanation of the observation that minor irregularities in the diurnal wave are rapidly smoothed out, so that the diurnal variation in soil temperature becomes more closely sinusoidal at greater depths.

For any given Fourier component with angular frequency ω , the amplitude of the soil temperature variation

$$A(\omega, z) = A_o(\omega) \exp(-z/D) \quad (6)$$

while the phase

$$\phi(\omega, z) = z/D \quad (7)$$

Where the homogeneous conductor model is valid, plotting the natural logarithm of the amplitude against depth gives a straight line whose gradient is $-1/D$, while a plot of the phase angle in radians gives a straight line with gradient $1/D$. Using equation (5) it is possible to derive two estimates of κ , which should be equal. Deviations from the homogeneous conductor model are immediately evident, either a failure to plot on a straight line, or as a discrepancy between the amplitude and phase estimates of κ . However, as will be demonstrated later this simple method, despite its assumptions, can provide useful results.

Further theoretical treatments are beyond the scope of this report but can be found in, for example, Physics of Plant Environment edited at W.R Van Wijk (1963) or in more recent text books which also include example values of the soil parameters.

(3) GEOGRAPHICAL VARIATIONS

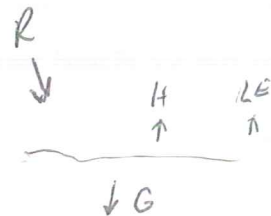
(3a) Background information

Over the last 25 years the Institute of Hydrology has carried out a wide range of experimental programmes in hydro-meteorology. The flux of heat into the soil, G , has been an important consideration in the energy balance for most surfaces which have been studied.

The surface energy balance equation is given by:

$$R_n - G = H + LE \quad (11)$$

where R_n is the net all-wave radiation balance and H and LE are the sensible and latent heat fluxes respectively. Other small terms associated with energy used for photosynthesis and heat storage in the vegetation growing on the surface can normally be neglected.



Soil heat flux is measured by means of flat thermopiles about the size of a coin buried in the soil quite close to the surface. The differential temperature between the two faces caused by the flow of heat creates a voltage which can be calculated and measured. In most cases profiles of soil temperature are also obtained to aid in understanding the soil heat transfer process and to provide thermal diffusivity and other information. Detailed descriptions of the sites, equipment and methods used will not be provided in this report but extended information can be obtained from the published papers cited at the end.

(3b) England

Several sites have been used for energy balance studies within the UK, but just two, with contrasting soil type and a wide range of vegetation covers, will be described in this section to give some idea of the sizes of the soil heat fluxes and temperature ranges that occur.

The research site at the Institute of Hydrology in Wallingford was equipped at various times with a wide range of energy balance sensors including soil instrumentation. The soil is a dense silty loam with stones. Figure (1) shows (for the end of April) the incoming solar radiation and net all-wave balance together with the soil heat fluxes for a bare soil area and areas covered with short mown grass and long natural grassland. Also shown are the associated soil temperatures at 10cm depths with air temperature for comparison. It is clear that the flow of heat into the soil on a sunny day is mainly driven by the input of direct beam solar energy to the surface. Under cloudy conditions the soil heat flux and temperature ranges are smaller and least affected by vegetation as they are mostly driven by ambient air temperature and residual soil temperature gradients.

Figure (2) illustrates the soil heat transfer process as outlined in the simple theoretical description earlier in the report. The measurements were made at the forestry area research site in Thetford and included soil measurements beneath four vegetation surfaces all growing on the same light sandy soil. The vegetation was short (rabbit mown) grass, heather, light forest (larch and pine) and a dense pine

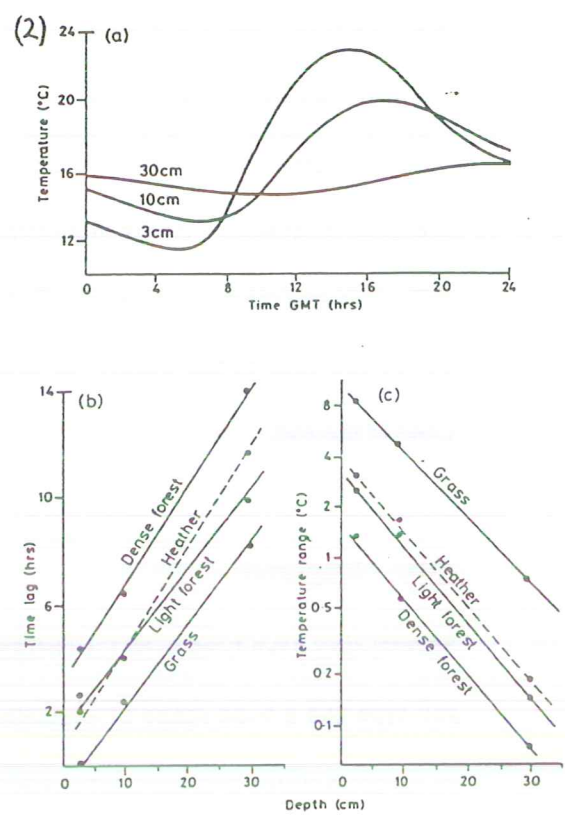
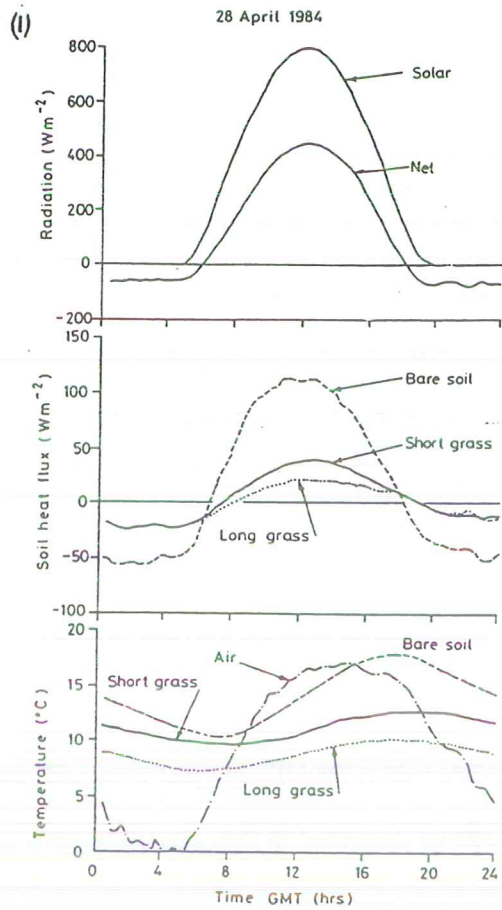


Figure (1) Soil temperatures and heat fluxes for three surface covers at Wallingford, England. Incoming solar radiation and net radiation measured above short grass are also shown.

Figure (2) (a) Soil temperature at three depths below short grass.
(b, c) Depth variation of the time lag of the occurrence of maximum temperature and of the diurnal temperature range for four surface covers at adjacent sites with the same sandy soil at Thetford, England.

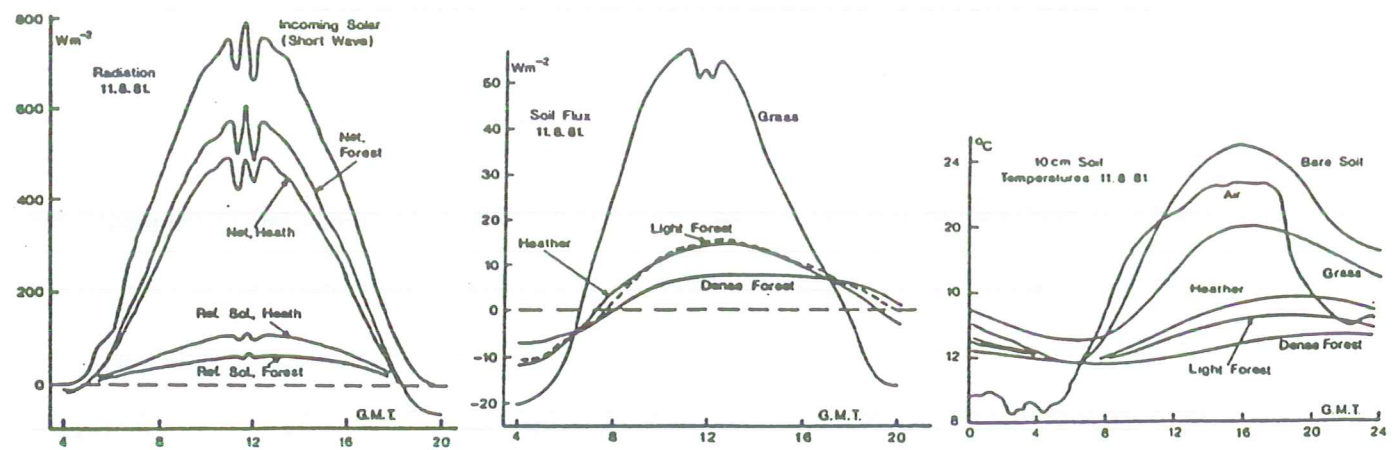


Figure (3) Radiation components, soil heat fluxes and 10 cm soil temperatures at Thetford, England.

plantation. The top graph shows the soil temperature measured at three depths beneath the surface, 3, 10 and 30 cm.

The two important facts are immediately obvious:- (i) the size of the temperature wave reduces with increasing depth and (ii) the time lag of the wave increases with depth. The other two graphs illustrate the method already described for determining the thermal diffusivity by plotting time lag or temperature range against depth. The time lag of occurrence of the maximum of soil temperature at 30 cm is shown to be as long as 14 hours in the case of dense forest which is associated with a temperature range of below 0.1°C . As the soil was about the same for all the vegetation covers the gradients of the lines are fairly equal and all give diffusivities in the region of $0.005 \text{ cm}^2 \text{ sec}^{-1}$. For the Wallingford site the values, derived by the same method, were around $0.004 \text{ cm}^2 \text{ sec}^{-1}$.

Figure (3) illustrates again the large contrasts between the sizes of the terms associated with the different vegetation covers for the Thetford site where plots similar to those in Figure (1) are presented for the various surface cover types.

(3c) Spain

During 1991 the Institute of Hydrology participated in the CEC funded "EFEDA" studies in central Spain. The work included measurements of soil heat fluxes and temperatures for two contrasting vegetation covers: vineyard and a sparse vetch crop - both planted on a calcareous cambisol soil with many stones in it.

As the soil was fairly exposed at both sites the soil heat fluxes were quite large and were therefore a significant component of the energy available for evaporation. The relative sizes of the energy components are illustrated in Figures (4) which show, for the vineyard, the averaged radiant energy values, together with the soil heat flux and sensible and latent heats from the surface for sunny days around late June when the vines were well developed. (It was necessary to make a large number of

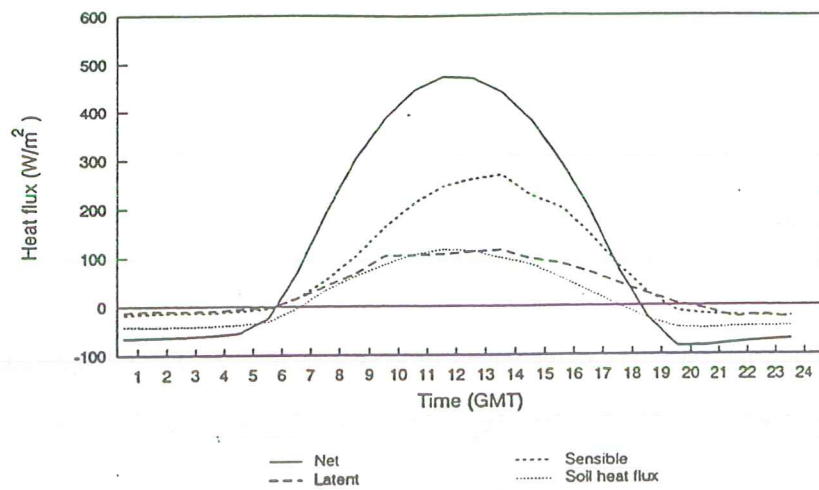


Figure (4) Mean radiation and heat fluxes for sunny days at the end of June for a well developed vine plantation in Spain.

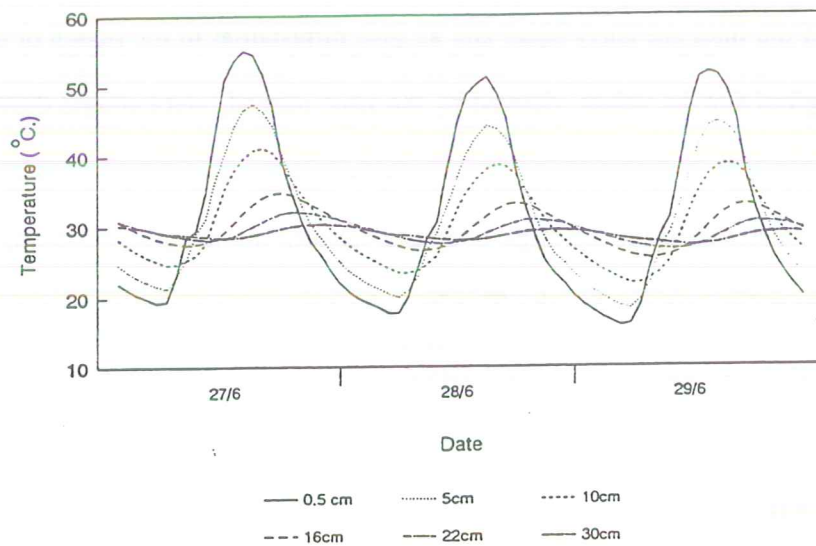


Figure (5) Soil temperatures at six depths for the Spanish vine site.

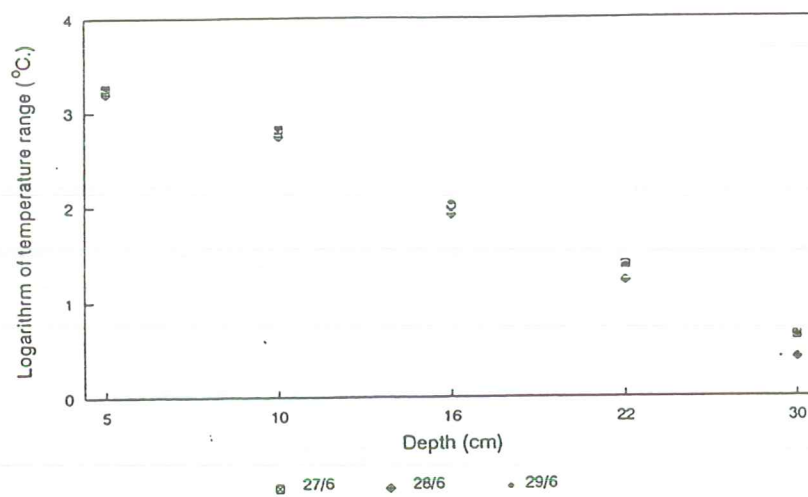


Figure (6) Plot of temperature range vs depth for the Spanish vine site.

soil heat fluxes and temperature measurements which had to be carefully weighted according to the areas of bare soil and vine cover to give the correct spatial averages.)

Figure (5) shows the soil temperatures at a range of depths from 0.5 to 30 cm for a sequence of three of the sunny late June days. It can be seen that close to the surface the soil temperatures exceeded 50°C - over 20°C more than the temperatures reached at 30 cm depth. Figure (6) shows a plot of temperature range against depth for these three days. Despite the stoney nature of the soil and other irregularities, at least below 10 cm a reasonable straight line gradient could be derived which gave a diffusivity value of around $0.003 \text{ cm}^2 \text{ sec}^{-1}$. The value for the more dense soil at the arable site was around $0.006 \text{ cm}^2 \text{ sec}^{-1}$.

(3d) Syria

Some measurements from a semi-arid site were made at the ICARDA centre in Syria in a barley field of vertic (calcic) luvisol soil which had previously been ploughed. The crop, which was planted on soil ridges, never achieved more than 50% cover. Soil heat flux plate arrays were used to give a spatial average and some limited measurements of soil temperature were also made.

Two days of results are shown for the area - before and after harvest. Figure (7) shows the energy components and Figure (8) shows the soil temperature at 16 cm depth together with the soil heat fluxes. For the two days shown for comparison the air temperature ranged from 9 to 26°C and 13 to 32°C respectively. The ratio of the soil heat fluxes in the middle of the day to the net all-wave radiation rose from 15% to 20% after the sparse crop was harvested so at all times was an important part of the energy flux calculation. The reduction in evaporation from the surface after harvest is also very obvious.

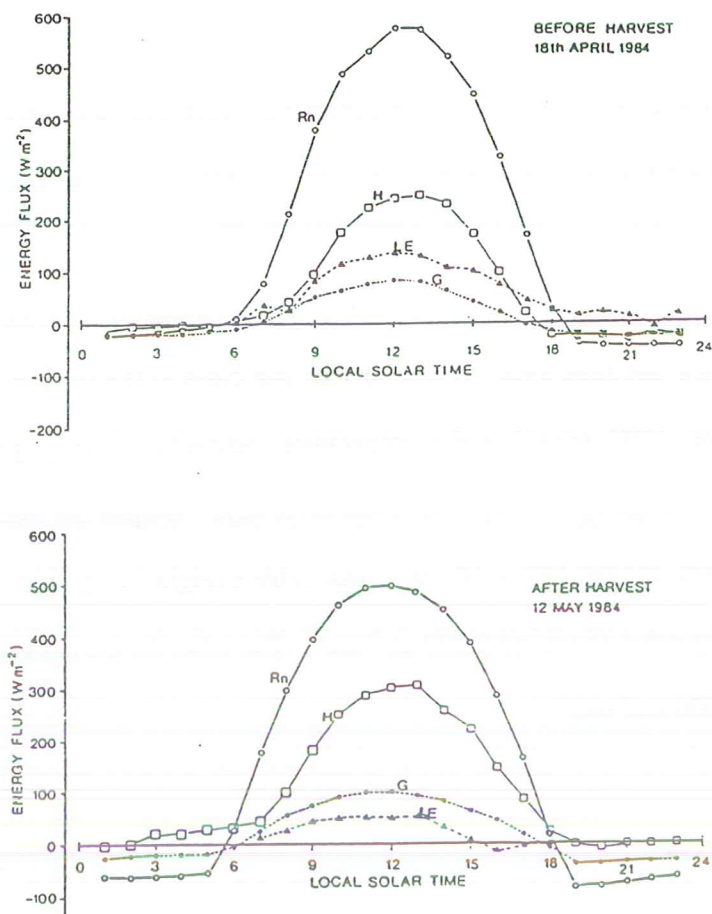


Figure (7) The diurnal variation in sensible (H) and latent (LE) heat fluxes over barley in Syria for two days, before and after harvest. Concurrent values of net radiation (R_n) and soil heat flux (G) are also shown.

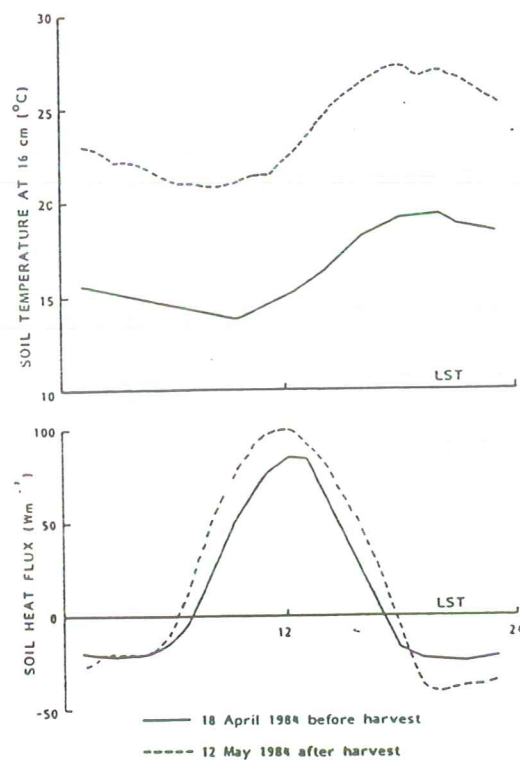


Figure (8) Soil heat flux along the crop ridge in Syria and soil temperature 16 cm below for 18 April and 12 May 1984.

(3e) Niger

Because of the recent concerns over desertification and the implications of climate change the Institute of Hydrology has carried out extensive studies in Niger.

The first site used was based at the ICRISAT Sahelian Centre near Niamey in a field of Dayobu sand over laterite gravel planted with a millet crop. In this area the average rainfall (concentrated between May and October) is about 560 mm. Figure (9) shows an example of the energy components both before and after harvest. The very high values of the soil heat flux for this area, even with the sparse millet crop present, are shown in Figure (10) together with the associated soil temperatures at three depths.

Subsequent studies have concentrated on two other areas, both also fairly close to Niamey. The first site was semi-natural fallow savannah with grass, woody shrubs and occasional trees on a very sandy 50 cm deep soil overlying laterite rock. The second site was degraded natural forest with strips of vegetation interspersed with bare soil (tiger bush). The soil here was sandy with many stones and less than 20 cm deep.

Figure (11) shows the radiation components together with the soil heat fluxes and 10 cm soil temperatures for a typical sunny day at the savannah site. The very marked reduction in the soil energy transfer caused by the presence of the denser and taller shrub/bush vegetation is very clear. There is a comparison between the two sites in Figure (12) which shows a day of data obtained the following year. Here the even larger contrast between the soil heat fluxes for the bare soil and forest area is seen.

(3f) Brazil

Work has been carried out at the Reserva Ducke natural tropical forest site near Manaus to measure the energy and water balances for use in climate models. Because they were such a very small part

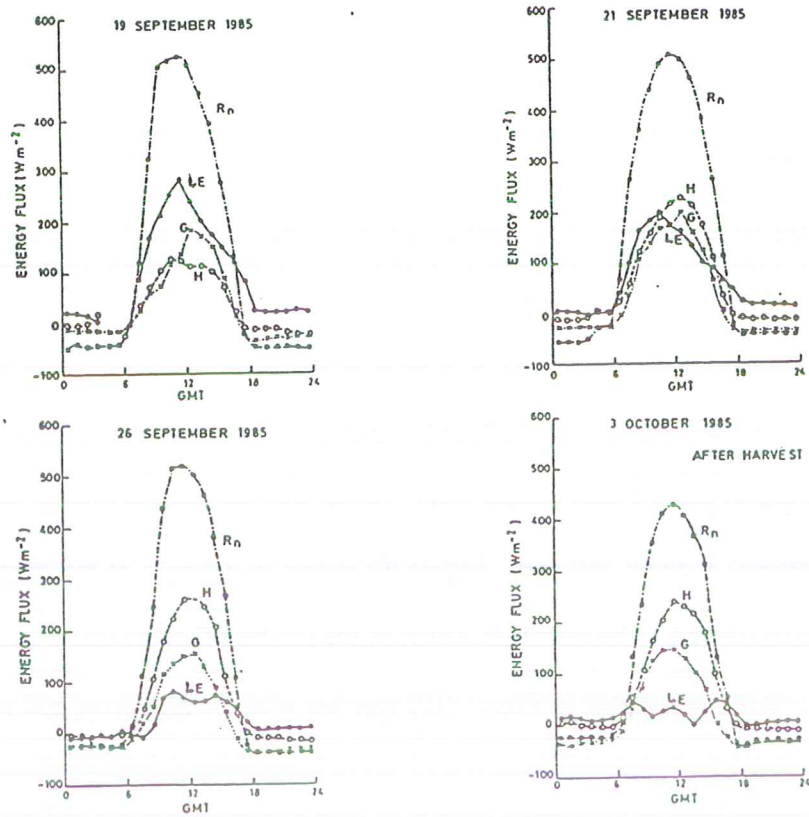


Figure (9) A series of days showing the changing energy balance of a millet crop in Niger. The four main components are net radiation (R_n), sensible heat (H), latent heat (LE) and soil heat fluxes (G).

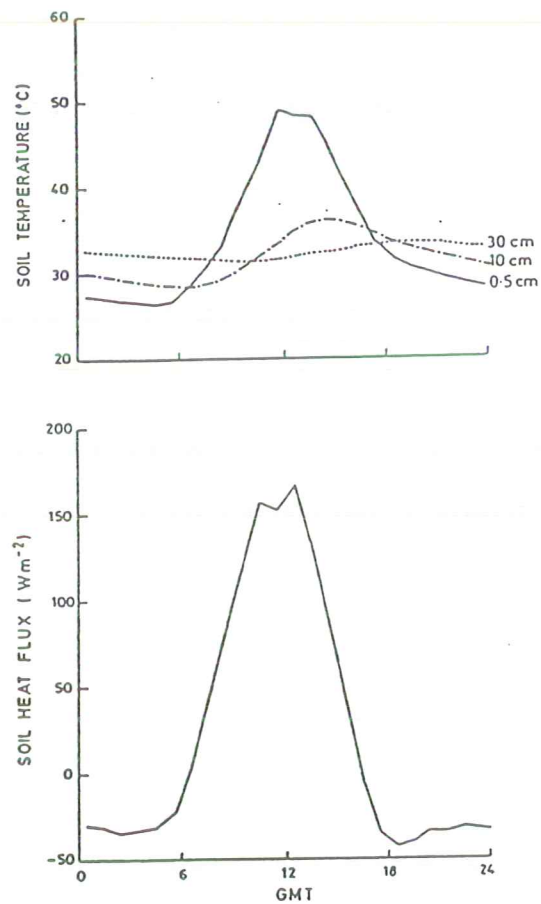


Figure (10) A typical example of the diurnal change in soil heat flux and temperature at 0.5, 10 and 30 cm under a millet crop in Niger.

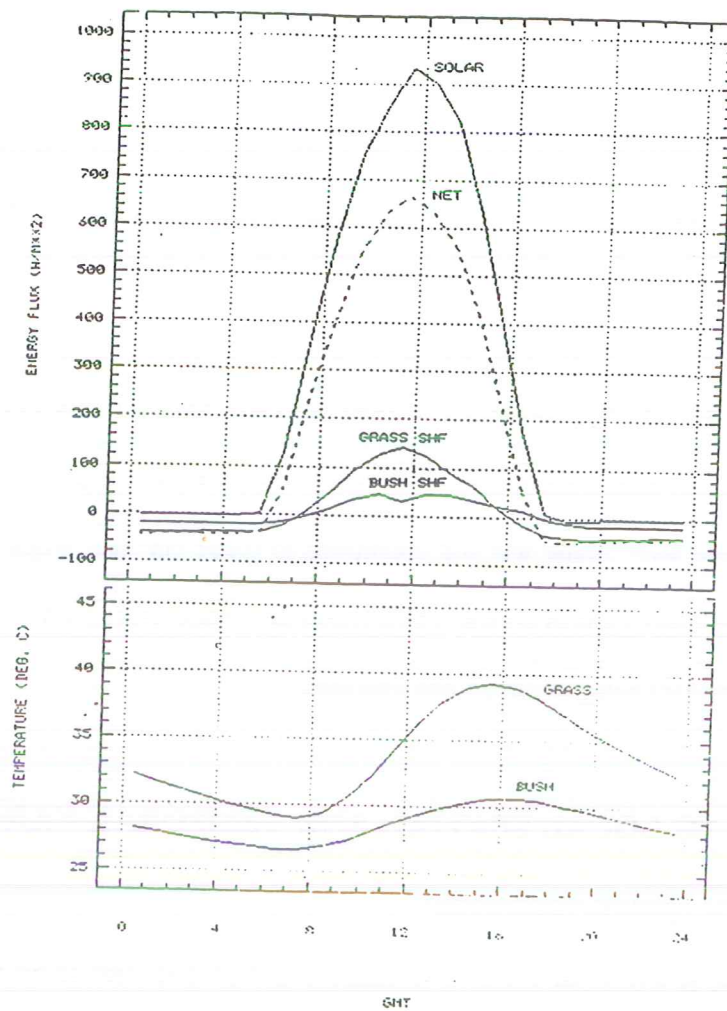


Figure (11) Diurnal variation of solar and net radiation measured at the savannah site in Niger, together with mean soil heat flux (SHF) and 10 cm depth soil temperature measured beneath both grass and bush cover, 18 October 1988.

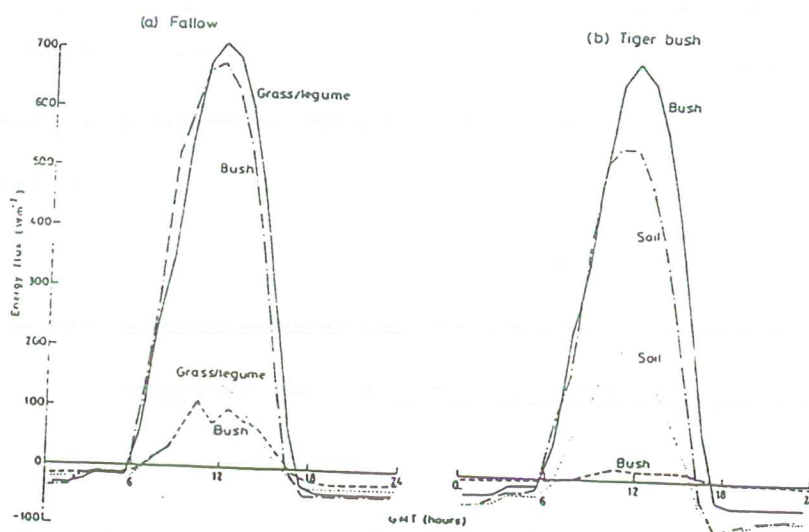


Figure (12) The components of net radiation, (— and ---), and soil heat flux (. . . and . . .) at the (a) fallow savannah and (b) tiger bush site in Niger on 11th October 1989.

of energy considerations on soil heat measurements were relatively unimportant. However the latest studies now include data collection at forest clearing sites where soil heat fluxes and soil temperatures are far more significant.

Early results from the Fazenda Dimona ranch, also near Manaus, with a predominantly clay soil have produced thermal diffusivities, derived from soil temperature data at 5, 10 and 20 cm, ranging from over $0.003 \text{ cm}^2 \text{ sec}^{-1}$ under wet soil conditions to $0.002 \text{ cm}^2 \text{ sec}^{-1}$ when the soil was at its driest. Some early example plots of both soil heat fluxes and temperature are shown in Figure (13) but much of the data are still being collected and analysed.

(4) LOCAL SPATIAL AND TEMPORAL VARIABILITY

(4a) Basic spatial variations

Soil heat flux is a difficult variable to measure and all data need to be treated with some caution. Errors can occur for many reasons including from the sensing technique itself. A soil heat flux plate, if it is to work correctly, has to have the same thermal properties as the surrounding soil so it does not disrupt the heat flow pattern. As soils have different thermal conductivities and these can vary with soil moisture etc, this condition is not always satisfied. Positioning the plates can introduce errors due to the presence of stones or air gaps. To be strictly accurate a correction should be applied for the effect of the energy in the soil above the plate, and methods involving the combination of plates and temperature profiles can be used to derive more accurate soil heat fluxes. In very dry soils it is difficult to obtain good thermal contact and plates are sometimes inserted in a wet patch so the soil binds to them. Variation in vegetation or soil can also introduce large differences which need to be averaged out by means of careful and extensive sampling. This becomes especially complex for developing sparse large crops such as the vines in the Spain.

Figure (14) shows an example from the Niger savannah site of maximum and minimum soil temperature measured across a 100m transect where the large effect of vegetation variability is seen.

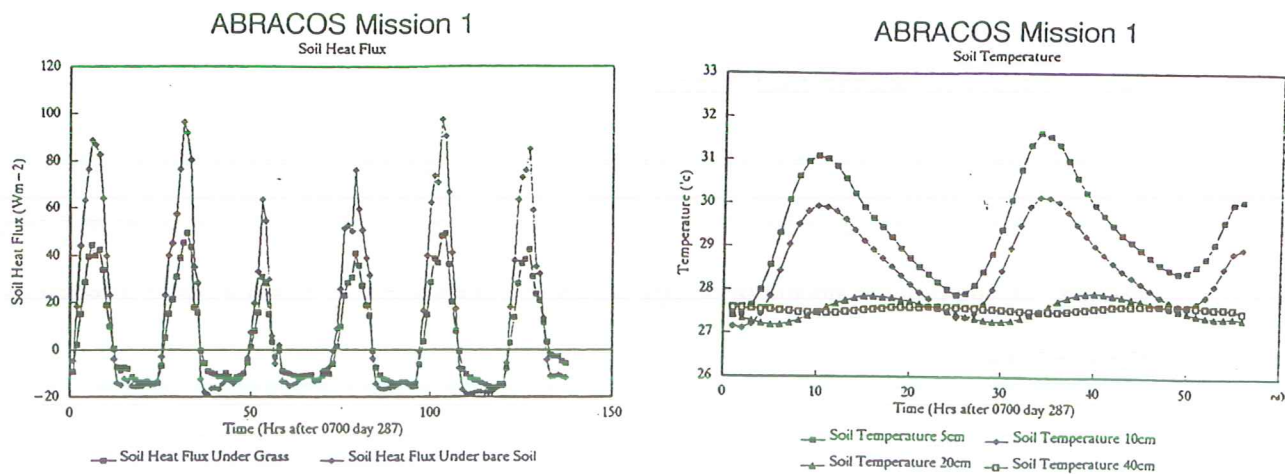


Figure (13) Soil heat fluxes beneath grass and bare soil for a series of days in a Brazilian forest clearing together with example soil temperatures beneath the bare soil for the first two days.

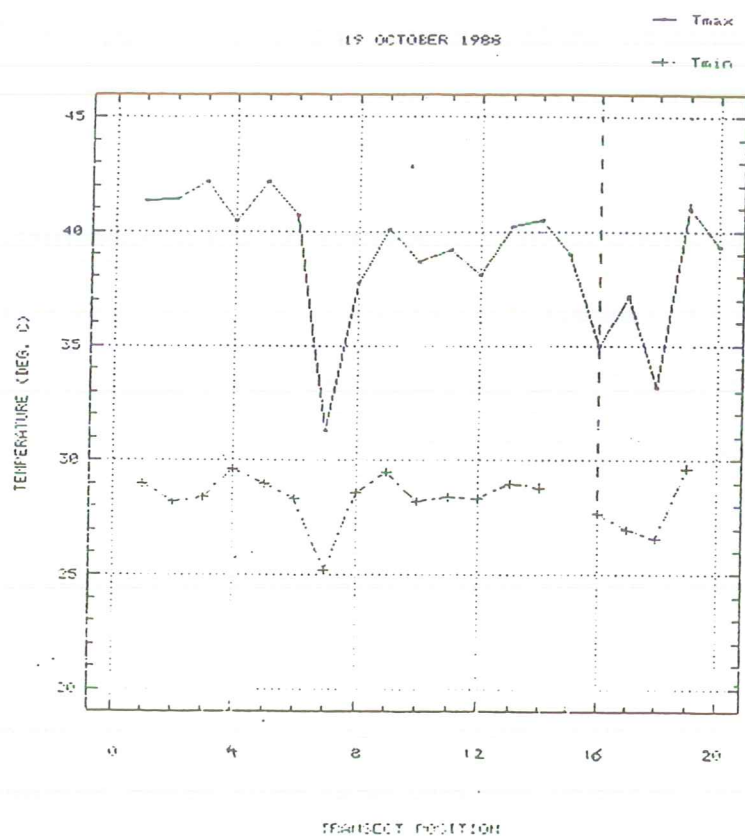


Figure (14) Maximum (T_{max}) and the minimum (T_{min}) soil temperatures as 10 cm depth measured at 5 m intervals along a 100 m transect in the savannah site in Niger on the 19 October 1988.

(4b) Effect of season and aspect

The proportion of available energy used for the various energy balance components in equation (11) will obviously vary for a variety of reasons through the year as the vegetation cover and climate changes. In addition the amount of energy available at the surface will be drastically affected by its slope and aspect.

An example of both these effects is demonstrated in Figure (15) which shows the net radiation, soil heat flux and soil temperatures at four depths for a 20° South facing slope and a 17° North facing slope in near mid-summer and mid-winter at an Institute research site on the chalky soil of the Chiltern hills near Oxford. Also shown in Figure (16) are the cumulative soil heat fluxes and soil temperatures for two slopes from December to July.

The dramatic contrasts between the slopes and with the season are very clear. These effects must not be forgotten when considering soil energy balances.

(4c) Seasonal effects of vegetation cover on soil temperatures

Studies of longer term variations of soil temperature have been made for the Institute of Hydrology sites in Plynlimon (Central Wales) and Thetford and just two illustrative results are presented here to demonstrate the relevance of such considerations.

Figure (17) shows how the mean 30 cm soil temperature at the Welsh site varied for spruce forest, grass in a large clearing and grass at a very open site. Large differences, especially between forest and grass in the summer, are demonstrated. Figure (18) shows the Thetford site for four vegetation covers and bare soil, the seasonal variation of the differences between mean daily air temperature and mean daily soil temperature demonstrating an increasing seasonal reversal of the trends as the vegetation cover amount decreased from the very dense Corsican pine site to the bare soil one.

Again such effects need to be borne in mind when considering soil temperature data.

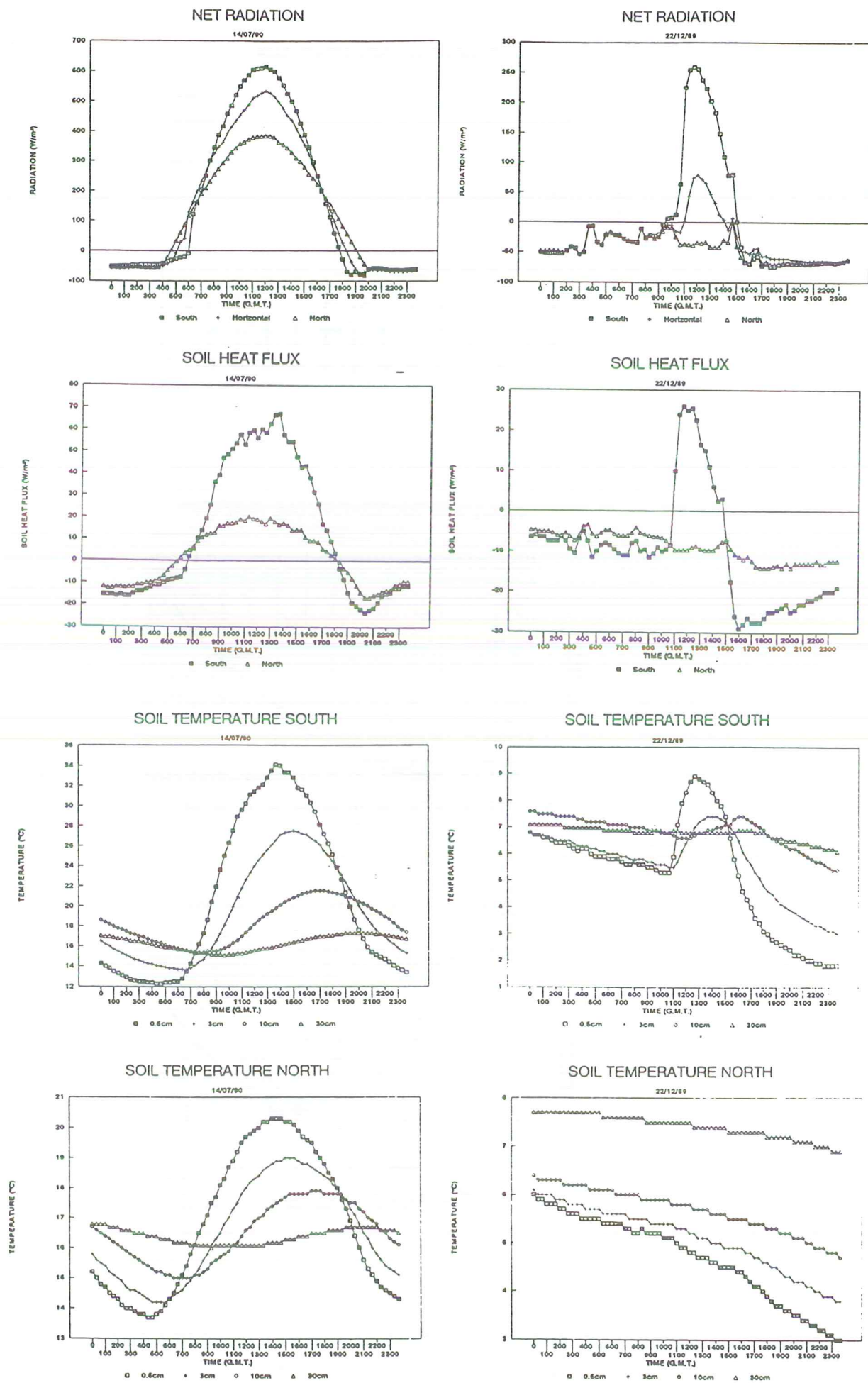


Figure (15) Radiation, soil heat flux and soil temperatures for the south and north slopes of a hillside near Oxford, England close to the summer and winter solstices

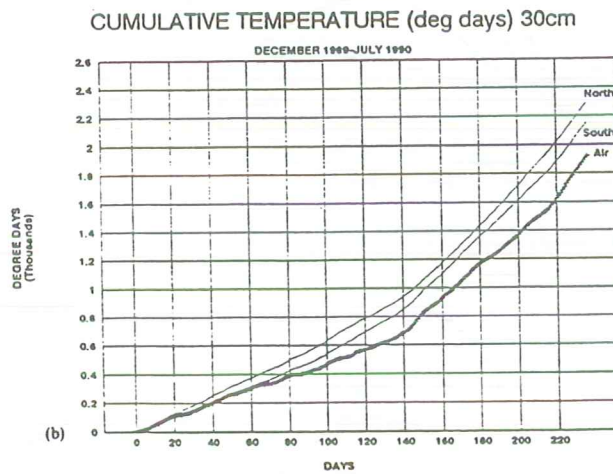
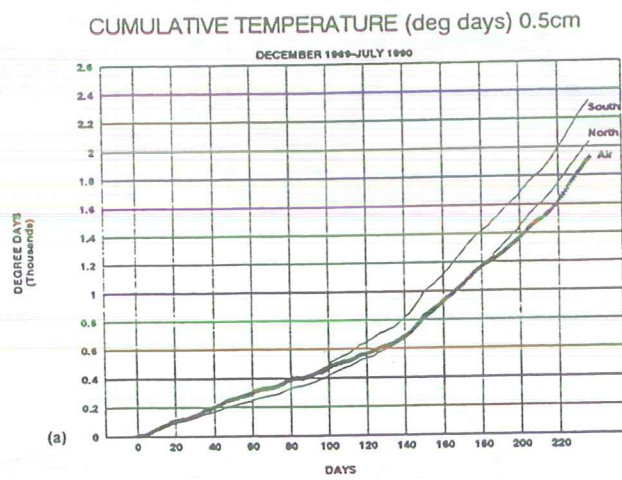
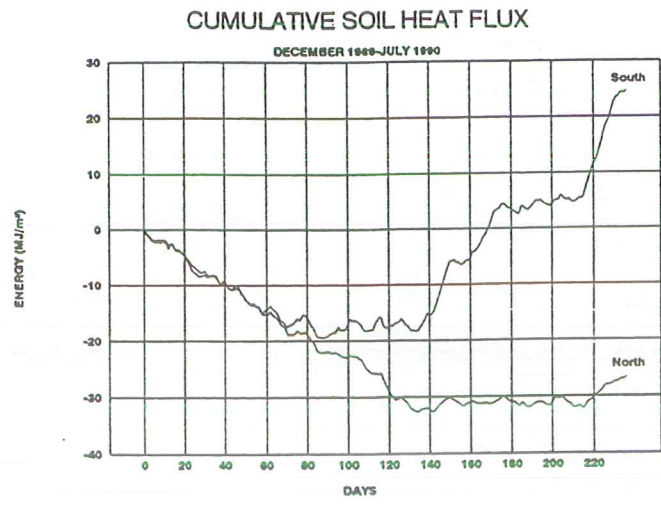


Figure (16) Cumulative soil heat flux totals, together with the mean daily soil temperatures at 0.5 and 30 cm for the south and north slopes and cumulative mean daily air temperature, measured on the north slope of a hillside near Oxford, England.

(4d) Altitudinal gradients of soil temperature

Studies of soil temperature data for a range of UK lowland and upland sites were carried out to investigate the importance of altitude. Figure (19) shows the seasonal variation of the differences in 0900 GMT 30 cm soil temperatures between a variety of lowland-upland station pairs, the differences being much greater in the summer. In Figure (20) the altitudinal gradients of both air and 30 cm soil temperature are shown for two high level stations with respect to a lowland one. The large change in soil temperature gradient with season can be contrasted with the relatively constant ($\sim 8^{\circ}\text{C km}^{-1}$) gradient for air temperature.

(5) SIMPLE LINKAGE BETWEEN SOIL HEAT FLUX AND TEMPERATURE

As there is an obvious need to be able to get some simple estimate of the possible size of the soil heat flux term in the energy balance equation the following method has been developed and tested for several of the Institute sites: As heat flows down into the soil it induces a temperature rise in proportion to it. Hence a relationship should exist between the daily positive soil heat flux component and the associated induced soil temperature rise. Data from various sites have been used with success to investigate this and examples from the UK and Syria are shown in Figure (21a) and (21b). Approximately linear relationships are found which are consistent enough to give reliable estimates through a range of soil moisture conditions and make a useful method of obtaining continuous soil flux estimates from simple temperature data.

(6) CONCLUSIONS

The extensive results presented in this report have aimed to demonstrate the importance of soil in the energy balance of the surface and the wide range of effects which give variability of soil temperature and soil heat flux. It is hoped that the data have given a useful indication of the range of soil thermal effects that may be encountered and which need to be considered in discussions of the ecological implications of the soil.

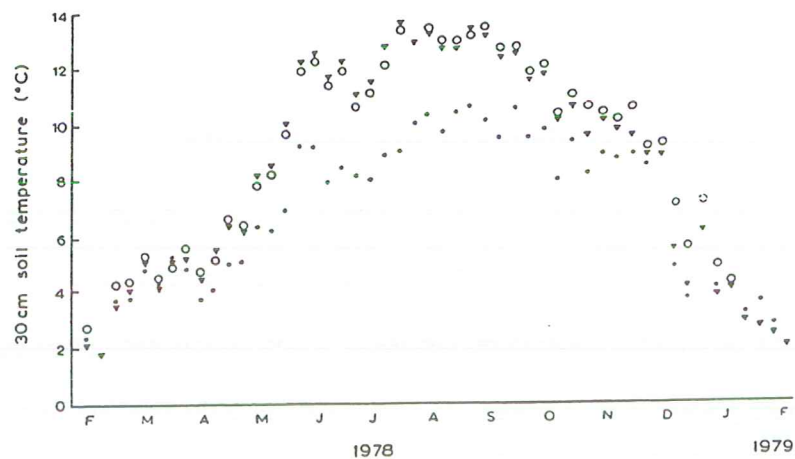


Figure (17) Variation during a 12 month period of 30 cm soil temperatures in upland mid-Wales, UK, at an altitude of 350 m. (* = spruce forest, v = grass in a large forest clearing, O = grass at completely open site).

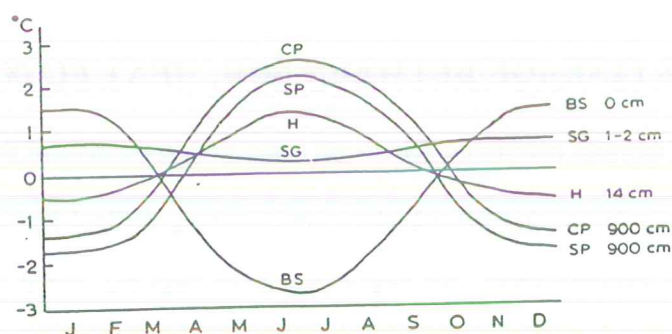


Figure (18) Difference between mean daily air temperature and mean daily 10 cm soil temperature over the period 1981-2 for all surface covers at Thetford, England, (BS = bare soil, SG = short grass, H = heather, CP = Corsican pine, SP = Scots pine; vegetation heights in cm).

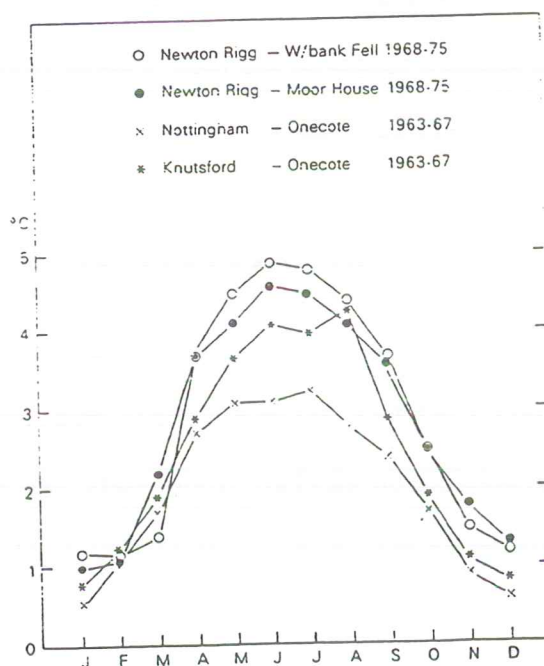


Figure (19) The difference between the mean 0900 GMT 30 cm soil temperature observations for four upland lowland pairs of station in, and around, the Pennines, England.

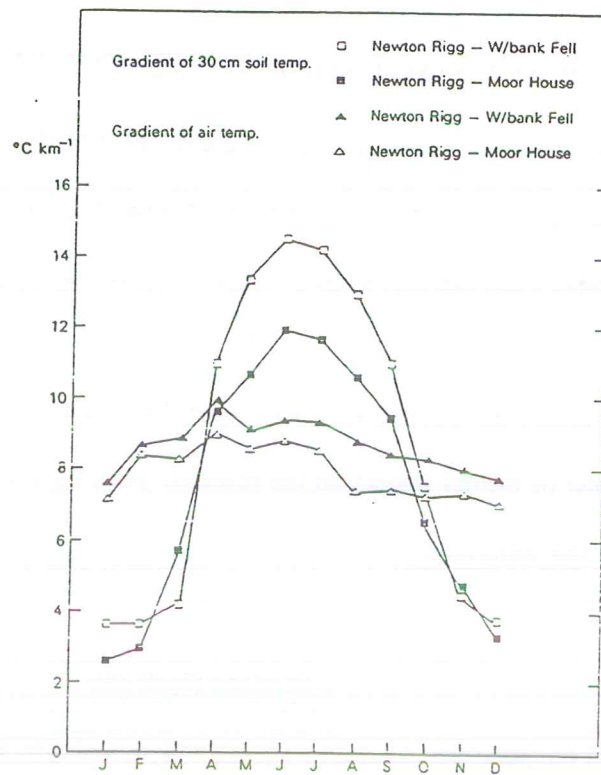


Figure (20) The altitudinal gradients of air and soil temperatures between two high-level stations in the Pennines, England, and a representative lowland station (Newton Rigg, alt. 171 metres, 1968-75).

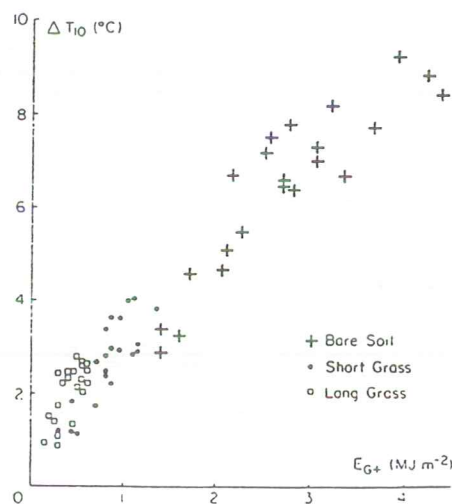


Figure (21a) Rise in soil temperature at 10 cm, ΔT_{10} , vs energy absorbed at the surface, E_{G+} , at Wallingford, England in 1984.

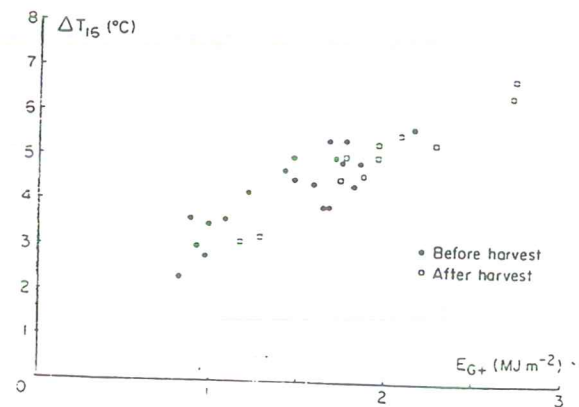


Figure (21b) Rise in soil temperature at 16 cm below crop ridge in Syria, ΔT_{16} , vs energy absorbed at the surface, E_{G+} , both before and after harvest in 1984.

(7) ACKNOWLEDGEMENTS AND REFERENCES

All the data presented were obtained by staff of the Institute of Hydrology. Many of the results have been taken from unpublished Institute or other internal reports, conference proceedings, or especially derived for this report and the use of these is gratefully acknowledged.

In addition the following published works have been used and these can provide additional information. (A list of further papers on the research work by Institute of Hydrology staff can also be obtained from the librarian).

Sections (3) & (5)

Soil heat flux and temperature variation with vegetation, soil type and climate - S. A. Oliver, H. R. Oliver, J. S. Wallace & A. M. Roberts. *Ag & Forest Met* 39 pp257-269, 1987

Vegetation and Hydroclimate - J.S. Wallace & H.R. Oliver in "Process studies in Hillslope Hydrology", ed M.G. Anderson & T.P. Burt. J. Wiley 1990.

Energy and water balances of developing vines - H. R. Oliver & K. J. Sene. *Ag & Forest Met* in press 1992

Section (4)

The effect of altitude on soil temperature - F. H. W. Green and R. J. Harding. *Met Mag* 108 pp 81-91, 1979

The relationship of soil temperature to vegetation height - F. H. W. Green, R. J. Harding and H. R. Oliver. *J Clim* 4 pp 229-240, 1984

Studies of the surface energy balance of sloping terrain - H. R. Oliver. *Int J Clim* 12 pp 55-68, 1992

METHANE EMISSION FROM PADDY SOILS IN JAPAN AND THAILAND

Makoto KIMURA (Nagoya University, Japan)

This discussion paper consists of two parts, CH₄ production and its fates in paddy soils.

First, the potential CH₄ and CO₂ production in Japanese and Thai paddy soils is estimated from chemical properties of paddy soils, their acreage and thermal regimes during rice growing period (voluminous information on which is available for many kinds of soils). As the carbon source of CH₄, there can be considered three major sources; i.e. soil organic matter, applied organic materials such as rice straw and manure, and rice plant (roots). Their relative contributions to the total CH₄ emission are estimated. In connection to the matter, the quality of rice straw and its incorporation site are considered further. Leaching rate and kind of fertilizers and their application (topdressing) method are also evaluated.

CH₄ emitted to the atmosphere is small portion of the total produced in paddy soils. It is partly oxidized in plow layer at rhizosphere and non-rhizosphere sites. Leaching to subsoil is an alternative route of its transfer from plow layer. CH₄ leached from plow layer is also oxidized in part in subsoil, and it is detected in underground water of agricultural use. CH₄ oxidation at respective sites and its transfer are estimated quantitatively and qualitatively.

Thus in this discussion, the dynamics of CH₄, its various fates, in paddy fields are emphasized more than the quantitative estimation of CH₄ fluxes to the atmosphere from paddy soils. The fates of CH₄ in paddy fields are summarized in Fig. 1. Processes with diamond marks are discussed in this paper.

I. ESTIMATION OF POTENTIAL CH₄ AND CO₂ PRODUCTION IN JAPANESE AND THAI PADDY SOILS

The potential CO₂ and CH₄ production in Japanese paddy fields were estimated from chemical properties of paddy soils of respective soil series, their acreage and thermal regimes during rice growing period (KIMURA ET AL 1991a). Total carbon mineralization (CO₂ plus CH₄) was calculated from the estimation of nitrogen mineralization of soil organic matter under anaerobic incubation. The assignment of mineralized carbon to CH₄ portion was calculated from the ratio of oxidation capacity, represented by free iron content of soil, and reduction capacity, represented by estimated NH₄ production during rice growing period.

METHODS OF CALCULATION

a) *Nitrogen Mineralization under the 'Standard' Anaerobic Condition:* The amount of nitrogen mineralized under the 'standard' anaerobic incubation period (30°C, 10 weeks) was estimated by the following equation (YOSHINO AND DEI 1977).

$$Y = 1.70 + 17.5x_1 + 0.444x_2 - 0.233x_3 - 1.58x_4 \quad (\text{eq. 1})$$

where Y : the amount of ammonium nitrogen mineralized

x₁ : the total nitrogen content (%)

x₂ : the amount of CEC (meq/100g soil)

x₃ : the amount of exchangeable Ca (meq/100g soil)

x₄ : the free iron content (%)

b) *Nitrogen Mineralization of Soil under Different Temperature*

Condition: Mineralization of soil organic nitrogen is also known to be expressed by the following equation (YOSHINO AND DEI 1977, DEI AND YAMAZAKI 1979)

$$Y = k[(T-15)D]^n \quad (\text{eq. 2})$$

where Y : the amount of ammonium nitrogen released (mg/100g soil)

K : the coefficient relating to the potential of mineralized nitrogen

T : incubation temperature ($^{\circ}\text{C}$)

(T-15) : the effective temperature above 15°C

D : the duration of incubation (days)

n : a constant relating to the pattern of ammonification
($n=0.7-1.0$)

For the estimation of the amount of nitrogen mineralized during rice growing period in respective paddy field, the mean transplanting and harvesting date of each prefecture, and the summation of effective temperature were referred to the data book (STATISTICS AND INFORMATION DEPT. 1977). Then it was calculated from the proportion of respective summation of effective temperature to the standard one ($1,050^{\circ}\text{C}$). As the proportion is dependent on the 'n' in eq. 2, it was supposed to be 0.7 and 1 here, because the 'n' usually falls in the range between 0.7 and 1.0 (YOSHINO AND DEI 1977).

c) Estimation of Carbon Mineralization under Anaerobic Condition: The amounts of carbon mineralized was estimated from the nitrogen mineralized by the factor of 10.8 (INUBUSHI AND WADA 1988).

d) Estimation of CH_4/CO_2 Ratio of Mineralized Carbon: TAKAI (1961) incubated the paddy soils under anaerobic condition and found the good correlation ($r=0.973$) between the ratio of produced CH_4 to CO_2 , and the ratio of "oxidation capacity" to "reduction capacity" of soils. He termed the "oxidation capacity" as the sum of the amounts of O_2 and NO_3 in the soil plus the produced ($\text{Mn}^{2+} + \text{Fe}^{2+}$) during incubation. NH_4 produced during incubation was termed as "reduction capacity". In replacing his "oxidation capacity" with free iron content in soil, better correlation was found between free iron content and "reduction capacity" ($r=0.995$), and the correlation equation was,
(CO_2/CH_4) ratio =

$$289[\text{free iron content}(\%)/\text{reduction capacity}] + 7.10 \quad (\text{eq. 3})$$

e) Amounts of CO_2 and CH_4 Production from Japanese Paddy Fields: The National Project entitled "Soil Survey for Maintenance of Farmland Fertility in Japan" was conducted during 1959-1978 to survey the soil properties of arable lands, both paddy fields and upland fields, in Japan. Farmland soils were classified into the 15 Soil Series Groups (SSG), and then into Soil Series. Total 210 Soil Series were recognized in the Japanese paddy soils in the Project. The representative sites of paddy fields and upland fields of each Soil Series were chosen in each of 47 prefectures. Their total number scored 3,343. Several soil properties of the representative sites were tabulated in the final report of the Project, including soil depth of Apg horizon, bulk density and the acreage of the soil series in the prefecture (ODA ET AL 1987).

From the database of each representative paddy field, the amount of nitrogen mineralization during the standard incubation

condition (30°C, 10 weeks) was first calculated by the eq. 1 (Step 1). Then it was corrected to that under the mean temperature condition of the respective soil using the eq. 2, where the 'n' was supposed to be 0.7 and 1 as mentioned before (Step 2). The amount of carbon mineralization was estimated by multiplying the amount of nitrogen mineralization with 10.8 (Step 3). It was assigned to CH₄ and CO₂ from the ratio obtained by eq. 3 (Step 4). Considering the bulk density of soil, the depth of Apg horizon and the acreage of the paddy field in a prefecture, the total amount of CO₂ and CH₄ emission from 15 SSG were calculated for each prefecture, then for 8 Japanese Districts and for all over Japan (Step 5).

RESULTS AND DISCUSSION

1) Total Amounts of CO₂ and CH₄ Production

Tables 1-1 and 1-2 show the estimated CO₂ and CH₄ production from plow layers of each SSG in 7 Districts. When calculated with n=0.7, the estimated amounts of CO₂ and CH₄ production due to the decomposition of soil organic matter were higher in the northern Districts and lower in the southern Districts than those calculated with n=1. But their difference was very narrow, so the following discussion was based on the data with n=1 except for the special comment. The potential CO₂ and CH₄ production from nearly all over 7 district paddy fields amounted to 3.38x10⁶ and 8.53x10⁴ ton C/one crop season, respectively. The simple extrapolation of these values to the total Japanese paddy fields suggested the production of 3.78x10⁶ CO₂ and 9.45x10⁴ CH₄ ton-C/one crop season. Gray Lowland Soil SSG produced most (38% and 41% of the total CO₂ and CH₄ production), followed by Gley Soil SSG (26% and 19%) and Wet Andosol SSG (16% and 19%) in this order.

2) CO₂ and CH₄ Production Per the Unit Area

Fig. 1-2 and 1-3 show the estimated amounts of potential CO₂ and CH₄ production per the area of 1 hectare. The amounts were different among 7 Districts, among SSG and among respective SSG of different Districts.

The District averages of CO₂ production ranged within 1.35 and 1.70 ton-C/ha and they showed the slight increase as the District locates more south. The difference between the maximum and the minimum of the District averages was less than 26%. The CO₂ production was highest in Gleyed Andosol SSG (2.31 ton-C/ha), followed by Andosol SSG (2.19 ton-C/ha), Wet Andosol SSG (2.11 ton-C/ha). When calculated with n=0.7, Andosol SSG showed the highest CO₂ production (2.61 ton-C/ha), followed by Gleyed Andosol SSG and Wet Andosol SSG. On the other hand, the production was lowest in Peat Soil SSG (1.22 ton-C/ha), followed by Gley Soil SSG (1.29 ton-C/ha) and Gray Lowland Soil SSG (1.38 ton-C/ha).

The District averages of CH₄ production were between 24.1 and 53.7 kg-C/ha, and they increased sharply as the District locates more south. Further differences were found among SSG and among respective SSG of different Districts. The CH₄ production was highest in Gleyed Andosol SSG (75.0 kg-C/ha), followed by Wet Andosol SSG (63.8 kg-C/ha) and Brown Lowland Soil SSG (43.6 kg-C/ha). On the other hand, the CH₄ production was lowest in Dark-red Soil SSG (18.2 kg-C/ha) and Gley Soil SSG (24.6 kg-C/ha).

Therefore it can be noted that the CH_4 production is influenced more significantly by the temperature during the rice growing period and by the type of SSG than the CO_2 production.

As mentioned before, the amounts of CO_2 and CH_4 production estimated in this report are the potential ones, and they will be widely fluctuated according to the ways of agricultural management. But as shown in eqs. 1 and 2, the decomposition amounts of soil organic matter, therefore the total amounts of CO_2 and CH_4 production, are primarily determined by the soil chemical properties and the temperature, and not by the ways of agricultural management. The agricultural management such as water management, e.g. mid-summer drainage and intermittent irrigation, may only influence the ratio of produced CO_2/CH_4 . The water management to make the paddy soil more oxidative increases the CO_2 production and decreases the CH_4 production.

3) Potential CH_4 and CO_2 Production in Thai Paddy Soils

Paddy soils in Thailand used in the present estimation were ones collected during 1970-1973 to cover various kinds of soil groups and relatively important paddy soils in the main rice growing area, including 65 profiles in the Central Plain, 43 in the Northeastern Region, 36 in the Northern Region, and 24 in the Southern Region (Fig. 1-1), thus from throughout the whole country (MOTOMURA ET AL 1979). Due to the lack of database for estimation in some soils, the following estimation was done with 146 soils out of total 169 soils. As the data on the respective areas they occupied were not available, only the CH_4 and CO_2 emissions derived from soil organic matter were shown per the unit area basis in Table 1-1. Their average emission amounts from respective soils in each Region and from the paddy soils in the whole Thailand were the simple mean of the amounts of all investigated soils. In addition, the irrigation system in Thailand has been still facilitated only in small area, so the planting and harvesting calendar fluctuates widely area to area, and year to year depending on the precipitation; e.g. June-July, June-August, May-June and September-November for planting season, and November-February, November-January, November-January and March-May for harvesting season in the Central Plain, Northeastern, Northern and Southern Regions, respectively (THE RICE RESEARCH INSTITUTE 1986). In the evaluation, the following calendar was adopted as the representative of transplanting and harvesting dates; middle of June, middle of July, beginning of August and beginning of October as the transplanting date, and end of November, end of October, end of November and end of February as the harvesting date in the Central Plain, Northeastern, Northern and Southern Regions, respectively.

The regional averages of CO_2 production ranged within 0.90 and 3.02 ton-C/ha ($n=1.0$). Generally, paddy soils in the Northeastern and Northern Regions were calculated to produce lower CO_2 than those in the Central Plain and Southern Regions. The difference between the maximum and minimum of the Region averages was 236 %, which was far wider compared with that of Japanese case (26 %). The CO_2 production was high in Marine Alluvial soils, Blackish Water Alluvial soils and Fresh Water Alluvial soils. While that from Hydromorphic Regosols and Hydromorphic Gray Podzolic soils was estimated to be low.

The mean of potential CO_2 production from Thai paddy soils was estimated to be 2.09 ton-C/ha/one crop season, which was 41 % higher than that from Japanese paddy soils. It was due mainly to the higher effective temperature (1786, 1355, 1377 and 1793 in the Central Plain, Northeastern, Northern and Southern Regions compared with 562 to 1267 in Japan).

The regional averages of CH_4 production were between 34.9 and 93.1 kg-C/ha ($n=1.0$). The same tendency among Regions observed in CO_2 production was recognized in CH_4 production (except for one Hydromorphic Gray Podzolic soil in the Northern Region). The difference between the maximum and minimum of the Region averages was 167 %, which in contrast with CO_2 production was smaller compared with that of Japanese case (236 %). Marine Alluvial soils and Blackish Water alluvial soils produced CH_4 more than Hydromorphic Non-Calcic Brown soils and Low Humic Gley soils. Fresh Water Alluvial soils showed the intermediate CH_4 production. The mean of potential CH_4 production from Thai paddy soils was estimated to be 66.4 ton-C/ha/one crop season, which was 78 % higher than that from Japanese paddy soils.

The high emission from marine and blackish water alluvial soils in Thailand contributed the relatively high CH_4 emission from Thai paddy soils. As discussed later, sulfate reduction processes are well known to suppress CH_4 production. As sulfates are generally rich in these soils and sulfates are considered to suppress CH_4 production in these soils, the values calculated here might be the ones overestimated. If so, CH_4 emission derived from soil organic matter in Thai paddy fields is considered to be comparable with that from soil organic matter in Japanese paddy fields.

According to BOUWMAN (1990), the world records on CH_4 emission during the rice growing season from paddy soils showed 90-510 kg-C emission/ha/one crop season. They are around 5 times larger in amounts than those in Tables 1-5 and 1-6. The lower values may suggest that fresh plant debris and root exudates contribute more to CH_4 emission in the paddy field, both of which were neglected in this estimation.

II. METHANE EMISSION FROM PADDY SOILS

1. SEASONAL VARIATION OF CH_4 EMISSION AND ITS MAIN CARBON SOURCES
2. SOIL TYPE AND MANURIAL HISTORY
3. MIDSUMMER DRAINAGE

The pot experiment was conducted to elucidate the effects of growth stage of rice plant, soil type (Brown Lowland Soil, Gray Lowland Soil and acid sulfate soil), manurial history and kind of fertilization on the CH_4 emission from paddy field (KIMURA ET AL 1991b).

MATERIALS AND METHODS

a) *Soils:* Two Japanese paddy soils (Anjo Yellow Paddy Soil: Dystrachrept and Fukushima Gray Lowland Paddy Soil: Typic Haploaquept) were used throughout experiments in the following sections. Anjo soil has been applied with the chemical fertilizer annually, and Fukushima soil for 15 years with chemical fertilizer or rice straw. Their chemical properties were shown in Table 2-1.

b) Cultivation of Rice Plant: Each of 3 kg portion of moist soils was put into a porcelain Wagner pot ($1/50 \text{ m}^2$), fertilized as shown in Table 2-2, then submerged and transplanted with 2 rice seedlings (*Oryza sativa* var. Japonica, KOGANEBAKE, 45 days old) on June 11, 1990. Non-planted pot was also prepared for each treatment. Pots were set in the open air. The heading date was on August 22.

To some of the pots with Fukushima soil of rice straw application were carried out the midsummer drainage for 5 days from August 6 to 11, then they were returned to the flooded condition and compared the CH_4 emission with those without midsummer drainage.

c) Measurement of CH_4 Emission: Figure 2-1 shows the layout of CH_4 emission measurement. Pot was placed into a plastic bucket and was submerged with deionized water, then acrylic pipe (diameter 25 cm, height 1 m) closed on one corner with acrylic plate was set onto the pot. Bottom end of the pipe was below water level to prevent the gas exchange from outside. Tedler bag (1 liter) was attached to the pipe to keep the inside pressure equal to the atmosphere. The inside air was directly introduced into the gas chromatograph equipped with a FID (GC-14APFF, Shimadzu Co. Japan) through the sample line selector. The selector with 6 channels enabled the measurement of CH_4 emission from 6 samples in a series of assay automatically with appropriate time interval (30 min to 1 hr).

RESULTS AND DISCUSSION

1) Seasonal Fluctuation of CH_4 Emission

Figure 2-2 shows the CH_4 emission from Anjo Paddy soil along the growth stage. The CH_4 emission from non-planted pots kept very low levels (less than 10 ug-C/pot/hr) and they were $1/3$ to $1/500$ of respective planted pots, irrespective of the treatments. Thus, the present result also supported the findings obtained by CICERONE AND SHETTER (1981) that rice plant is the main emission route of CH_4 to the atmosphere. Two exceptions were recorded on July 12 and 21 from rice straw applied pot (52 and 2580 ug-C/pot/hr , respectively). They were because the active decomposition of rice straw produced the CH_4 -rich bubbles and they became ebullient by the diurnal increase of soil temperature during measurement.

Among the planted treatments, the emission was far higher in the rice straw applied treatment than in other treatments up to the heading stage. The emission maintained the 600 to 1100 ug-C/pot/hr until the heading stage, and then they decreased gradually. Similar result of large CH_4 emission from rice straw applied pot was also observed by YAGI AND MINAMI (1990a). The methane emission from the chemical fertilizer pot increased steadily along the growth stage and it was kept at high level (315 - 800 ug-C/pot/hr) during its ripening stage. It was interesting that the manure pot, so-called "processed rice straw" applied treatment kept the similar pattern and emission to the chemical fertilizer treatment. The emission of no fertilizer treatment also showed the emission similar to the chemical fertilizer treatment in the early growth stage, but remained to the lower emission than other treatment during the late stage (100 - 200 ug-C/h/pot).

CH₄ emission from non-planted pot of Fukushima Paddy soil was also kept at very low level, far lower than those of respective planted pots (Fig. 2-3). As for the planted treatments of Fukushima Paddy soil, the emission was lower than those of Anjo Paddy soil in the early growth stage, but they increased to the similar level in the late stage. Figure 2-3 depicts the data of chemical fertilizer and manure treatments of Anjo Paddy soil to understand easily the similarity of the emission between both soils. Long-term rice straw applied soil emitted CH₄ twice as large as long-term chemical fertilizer applied soil.

2) Amounts of CH₄ Emission in Different Manurial treatments

In spite of the different manurial treatments and soil types, CH₄ emission and its pattern were similar each other after the heading stage (Figs. 2-2 and 2-3). So, the cumulative amounts of CH₄ emission were calculated separately before and after that stage (designated as A and B stages, respectively; Fig. 2-4). Since the experimental periods of A and B stages were nearly equal, namely 38 and 41 days, it was appropriate to compare the emission amounts during each stage.

In A stage, the emission amount was the largest in rice straw applied treatment of Anjo Paddy soil (39 g CH₄-C/m²) and it was larger than that recorded in B stage (33 g CH₄-C/m²). Other treatments of Anjo soil and two kinds of Fukushima soils gave low amounts each other (6-8 g and 3-7 g CH₄-C/m², respectively). On the contrary, in B stage all the treatments including the rice straw applied treatment gave similar emission amounts to rice straw applied treatment in A stage except for no fertilizer treatment of Anjo Paddy soil; Fukushima Soil 1=21 g, Fukushima Soil 2=45 g, Anjo Chemical Fert. Treatment 1=21 g, Fukushima Soil 2=45 g, Anjo Chemical Fert. Treatment=29 g, Anjo Manure Treatment=35 g, Anjo Rice Straw Treatment=33 g, and Anjo No Fert. Treatment=6 g CH₄-C/m², respectively.

From Figs. 2-2 and 2-3, it was noted that the main stage where the manurial treatments (rice straw, manure, and chemical fertilizer application) and the soil type (Anjo and Fukushima Paddy soils) were reflected on the CH₄ emission is in the early growth stage (A stage, before the heading stage), and that the CH₄ emission is similar each other but larger in the late growth stage (B stage, after the heading stage), irrespective of manurial treatments and soil type (except for the no fertilizer treatment). The findings observed in B stage suggested that the CH₄ emission in B stage is controlled by the rice plant itself, maybe by means of root exudation and slough-off, and that these sources take more important roles in CH₄ emission from paddy field. Very low CH₄ emission from no fertilizer treatment of Anjo soil, where the plant growth was very poor, also supported this inference.

3) Effect of Midsummer Drainage upon CH₄ Emission Rates

With drainage, CH₄ emission decreased drastically, and increased again, though gradually, after reflooding (Fig. 2-5). Measurement was conducted from the first day of drainage, August 6, to August 27, and the total emission amounts during this period were ca. one sixth of the corresponding continuously flooded treatment. Extrapolating the estimation of CH₄ emission as shown with dotted line in Fig. 2-5 indicated that the emission amounts from midsummer drainage pot were about half of that from

continuously flooded pot during August 6 to October 9. Figure 2-6 is the schematic conclusion of the present results, where the solid line shows the emission pattern of chemical fertilizer pot (as the control). With the application of organic materials to soil or in soil with much amounts of available microbial substrates, the uplift time of CH_4 emission shifts to the earlier stage, as observed in the rice straw applied pot, in Anjo soil. In the late stage, the CH_4 emission is similar to that of the control among different manurial treatments and different types of soils. From the viewpoint of greenhouse effect exerted by CH_4 emission, the B stage is more important because of much larger emission amounts. Thus the strategy of reducing CH_4 emission from paddy field is partly through the manurial treatment, which is the main controlling factor of CH_4 emission in the early stage, but mainly through the water management as observed in the summer drainage procedure.

END OF NITROGEN FERTILIZERS

SUPPRESSION OF CH_4 EMISSION BY FOLIAR SPRAY TOPDRESSING

Pot experiment was conducted to evaluate the effects of kind of ammonium fertilizers (ammonium sulfate, ammonium chloride and ammonium nitrate) and their method of topdressing (broadcasting and foliar spray) on the methane emission from paddy field (KIMURA ET AL 1991a).

MATERIALS AND METHODS

Cultivation of rice plant: Three kg of Fukushima soil (Typic Ustaquept) with basal fertilizers ($0.3 \text{ g-P}_2\text{O}_5$, $0.3\text{g-K}_2\text{O}$, and 0.3g-N as calcium superphosphate, potassium chloride and NH_4NO_3 (treatment 1), NH_4Cl (treatment 2) or urea (treatment 3) respectively) were submerged in pot and transplanted with two seedlings. Nitrogen fertilizers of respective form were topdressed twice by spraying their water solution (2.5-5%) from the top of rice plant (foliar spray) or broadcasting on soil surface.

Measurements: Methane emission from pots to the atmosphere was measured every two to six days around noon by the closed chamber method as described before (KIMURA ET AL 1991b). On the last day of growing, grain yield and number of ears were measured.

RESULTS AND DISCUSSION

Figure 2-8 shows the seasonal variation of methane emission from the broadcasting pots. Five days mean temperature of daily growing temperature was also shown in the Figure. Generally there was no correlation between temperature and seasonal methane emission, except in September when there was a positive correlation between them as was observed in an Italian rice paddy (APFEL-PSCHORN AND SEILER 1986, SCHUTZ ET AL 1989).

Methane emission remained to the very low level until around July, then it increased exponentially until the beginning of August. Though slower, it increased exponentially further during September, and tended to decrease in September. After the first topdressing, treatment 3 with urea fertilization recorded the lowest emission, then treatment 2 of NH_4Cl and treatment 1 of NH_4NO_3 in this order. The rapid decrease of CH_4 emission after topdressing was reported by YAGI AND MINAMI (1990b) in Japanese paddy fields. The effect of topdressing was also

observed in Texas paddy fields (SASS ET AL 1990). Thus the immediate suppression of methane emission by topdressing was common, but the total methane emission during one crop season was higher in topdressing treatment pot than in the treatment without topdressing (CICERONE ET AL 1983).

The influence of kinds of nitrogen fertilizer lasted about 20 days. At length, the difference of methane emission among treatments was not recognized around 3 August, when the second topdressing was practiced. The second topdressing also suppressed CH_4 emission in the first 3 days ($(\text{NH}_4)_2\text{SO}_4$ treatment pot) or between 3 and 5 days after topdressing (NH_4Cl and urea treatment pots).

Thus, the topdressing of SO_4 -containing nitrogen fertilizer suppressed the emission most. This might be due to the proliferation of sulfate reducing bacteria following the application of sulfate, which are the competitors of methanogenic bacteria on common substrates such as organic acids and hydrogen. It was known that the suppression of sulfate reduction increased methane production several times in the rhizosphere soil of rice plant (KIMURA ET AL 1991c).

As shown in Fig. 2-9, foliar spray of nitrogen fertilizers induced serious suppression of CH_4 emission in every treatment. Immediate suppression after topdressing was most severe in $(\text{NH}_4)_2\text{SO}_4$ treatment, while it was mildest in urea treatment. The suppression by foliar spray lasted longest in NH_4Cl treatment. It might be due to browning symptom of leaves and resultant growth restraint brought about by its foliar spray, though only small amount of applied fertilizer was considered to remain on leaves with the present method.

For comparison, total CH_4 emission from the time of transplanting to the harvest was calculated in Table 2-3. Figures in parenthesis were relative methane emission to $(\text{NH}_4)_2\text{SO}_4$ broadcasting treatment. Topdressing by foliar spray reduced CH_4 emission in each fertilizer treatment compared with respective broadcasting treatment: 45%, 60% and 20% reductions in ammonium sulfate treatment, ammonium chloride treatment and urea treatment, respectively. In comparison with $(\text{NH}_4)_2\text{SO}_4$ broadcasting, NH_4Cl and urea broadcasting increased CH_4 emission by 12 and 30%, respectively. While $(\text{NH}_4)_2\text{SO}_4$ foliar spray decreased them by 45%, but foliar spray of urea did not change CH_4 emission. SCHUTZ ET AL (1989) also found that urea application (as basal fertilization) emitted more CH_4 than $(\text{NH}_4)_2\text{SO}_4$ application. As for the effect of the type of fertilizer application on CH_4 emission, it was known that the surface application of $(\text{NH}_4)_2\text{SO}_4$ as basal fertilizer emitted CH_4 most, then application by rake and deep incorporation in this order (SCHUTZ ET AL 1989).

Fertilization is indispensable for intensive rice cultivation, which necessarily increases CH_4 emission from paddy fields (CICERONE AND SHETTER 1981; CICERONE ET AL 1983). It is known that the application of not only organic materials but also chemical fertilizers increases CH_4 emission (YAGI AND MINAMI 1990b; KIMURA ET AL 1991b), though adverse effect of chemical fertilizer on CH_4 emission was observed in an Italian paddy field (SCHUTZ ET AL 1989). As this research showed that the method of topdressing and the kind of nitrogen fertilizer influence CH_4

emission seriously, the methane flux rate to produce unit weight of grain was calculated in Table 2-4 from the total CH_4 emission and grain yield. It was least by $(\text{NH}_4)_2\text{SO}_4$ fertilization, then by NH_4Cl and urea fertilization in this order in both topdressing treatments of broadcasting and foliar spray. Compared with the present rate of urea fertilization (49.3-55.2 $\text{mgCH}_4\text{-C/g}$ grain), the rates in Texas paddy fields recorded 5.6-47.4 $\text{mgCH}_4\text{-C/g}$ grain (SASS ET AL 1991). As shown in Table 2-4, topdressing by foliar spray reduced the rate in each nitrogen fertilizer treatment compared with that by broadcasting. In this experiment, topdressing of $(\text{NH}_4)_2\text{SO}_4$ fertilizer by broadcasting might be said most appropriate when considered grain yield.

6. PERCOLATION RATE OF IRRIGATION WATER

The effect of percolation rate on the CH_4 emission to the atmosphere is described in detail in Section III-2 in relation with its effect on CH_4 leaching into subsoil. In summary, there was no effect of percolation rate of irrigation water on CH_4 emission in our experiment, though YAGI ET AL (1990) reported its depressive effect on the emission.

7. MAIN ROUTE OF CH_4 TRANSFER THROUGH RICE PLANT

As rice plant consists of many stems of different age, the CH_4 emission rate through stems of different age is considered to be different each others. In addition, rice straw and stubbles are heterogeneously incorporated, some are close to rice plant and the other far from it. As a root is known to supply nutrients and water to a respective stem from which it develops, CH_4 emission from each stem is expected to be different each other depending on the sites where associated roots locate. So pot experiment was conducted to compare the CH_4 emission from stems of a rice plant with different age, and stems which develop their roots to the site of rice straw incorporation and to the bulk soil.

MATERIALS AND METHODS

Experiment 1: Three kg of moist paddy soil (Typic Haploaquept) was put into pot, applied chemical fertilizers, submerged and then transplanted with 2 rice seedlings on June 11, 1990.

Rice plants at the tillering stage were used in this experiment (July 16). As it was known that stem cutting above water surface does not influence on CH_4 emission (SEILER ET AL 1984), CH_4 emission of two pots was first measured after all the stems of rice plant were cut above water surface (Fig. 2-10). Then a half of stems of one pot were cut further from younger stems below water surface (so CH_4 transfer to the atmosphere was only through older stems). While a half of stems of the other pot were cut further from older stems below water surface (CH_4 transfer was only through younger stems). Both pots were again measured the methane emission rate. The time spent from the first measurement to the end of the second measurement was less than 3 hours.

Experiment 2: Three kg of Anjo soil (Dystrochrept) in pot was separated vertically into two by a plastic plate (Fig. 2-11), and 0.75g of chopped rice straw was mixed with one side of soil. A rice seedling was transplanted to cross over the plastic plate.

Thus tiller roots developed equally in both sides. On CH_4 measurement, acrylic pipe with two compartments was set onto the pot, one compartment covered stems growing in soil with rice straw and the other covered stems growing in soil without rice straw (Fig. 2-11). CH_4 measurement procedure was the same as described in Section II-1.

RESULTS AND DISCUSSION

Experiment 1:

The cut of older stems below water surface decreased the CH_4 emission rate less than half of the first measurement, while the cut of younger stems did not influence the emission rate, which suggested the main transfer route of CH_4 to the atmosphere was through older stems of rice plant in the early growth state (Fig. 2-12).

Experiment 2 Results are summarized in the supplement paper.

III. CH_4 PRODUCTION AND ITS FATE IN PADDY SOILS

1. ANAEROBIC CH_4 OXIDATION IN NON-RHIZOSPHERE SOIL OF PLOW LAYER

Soil is a highly heterogeneous environment for microorganisms. Some parts are rich in their substrates, e.g. rhizosphere and plant debris, and others are poor in them, e.g. sand grains. So microbial activities are expected to be different at each respective part. In the paddy field, it is well known that nitrification carries on at the oxidized shallow layer, while denitrification goes on in reduced part just below the oxidized layer (UEHARA ET AL 1978). Production and oxidation of CH_4 are also expected to occur at different site each other. As the sites of CH_4 oxidation in the paddy field, rice rhizosphere (HOLZAPFEL-PSCHORN ET AL 1986, HOLZAPFEL-PSCHORN AND SEILER 1986) and soil-water interface (HOLZAPFEL-PSCHORN ET AL 1986) were considered. It was estimated to extend to 0-30% of the produced CH_4 in the paddy field and to 67-80% in small pot experiment by their estimation. Oxidation of CH_4 in surface water was considered to be negligible (SEILER ET AL 1984). These CH_4 oxidations are by aerobic processes. Anaerobic oxidation of CH_4 is another important process for its fate in paddy field. Here model experiment was conducted to clarify the CH_4 production and decomposition (anaerobic oxidation) sites in plow layer of paddy fields.

MATERIALS AND METHODS

a) Preparation of Soil Column and Collection of Leachate: One hundred and fifty gm of Anjo (Dystrochrept) was mixed with pulverized rice straw at the concentration of 0, 0.3 and 0.6%. Two soils with different concentration of rice straw were packed into a glass column (diameter: 7 cm) to consist of two layers. The combination of two layers are shown in Table 3-1. Thin layer of quartz sand (ca. 20 mg) was inserted between two layers to distinguish each layer. As shown in the Table, single layer soil column with 0 and 0.6% % rice straw was also prepared for the check.

The column was kept at 25 °C under dark condition. Eighty ml of leachate was collected every 3 days with a glass syringe. On collecting leachate, first and last 20 ml leachate was discarded and intermediate 40 ml was used for analyses.

b) Analytical Methods: CH_4 concentration in leachate was deter-

mined by gas chromatograph (KIMURA ET AL 1992b).

RESULTS AND DISCUSSION

Time course of CH_4 concentration in leachate of each treatment is shown in Fig. 3-1. CH_4 concentration in leachate of treatment 1, soil without rice straw, was very low throughout the incubation period, while it increased sharply from day 6 in treatment 2 and reached the saturation level on day 21 and afterward. So it was known that the site rich in rice straw was the main site of CH_4 production.

The result that CH_4 concentration in leachate of treatment 4 was slightly lower than that of treatment 2 during early incubation period suggested that the percolation with anoxic soil water instead of oxalic distilled water did not increase CH_4 production.

The result that CH_4 concentration in leachates from treatments 2 and 4 was higher than that from treatment 5 showed the CH_4 decomposition at the lower part of soil in treatment 5, where it was poor in decomposable organic material (rice straw). This decomposition (oxidation) was an anaerobic process, because the leachate from treatment 2 contained Fe^{2+} ion from day 9.

As CH_4 concentration in leachate from treatment 3 was lower than those from treatments 2 and 4, and similar to treatment 5, it was considered to be due to the lower CH_4 production and/or the coexistence of production and decomposition in this treatment soil.

2. LEACHING OF CH_4 INTO SUBSOIL

Generally only the emission to the atmosphere have been paid special attention on the transfer of methane produced in paddy fields. It is known that both inorganic components such as Fe^{2+} and Mn^{2+} , and organic components such as water soluble saccharides were transferred with percolating water from plow layer into subsoil in paddy soil. In this context, CH_4 was also known to transfer into subsoil with percolating water (INUBUSHI ET AL 1992).

This experiment was aimed to confirm the transfer of CH_4 into subsoil with percolating water as affected by rice straw application (Experiment 1) and to clarify effects of percolation rate on CH_4 transfer (Experiment 2) (KIMURA ET AL 1992b).

MATERIALS AND METHODS

Three hundred grams of moist paddy soil (Typic Haploaquept) was mixed with pulverized rice straw (RS: 0, 0.3, 0.6 and 1.0% w/w), packed into a glass column (diameter: 7 cm, height: 12 cm), and then submerged at 25 C (Experiment 1). For evaluating the effect of percolation rate on CH_4 leaching, the 0.6% RS added soil mentioned above was used (Experiment 2).

In Experiment 1, 60 ml of leachate was collected every 3 days. While in Experiment 2, three different volumes of leachate, 30, 60 and 120 ml, which corresponded to 0.26, 0.52 and 1.0 cm/day water requirement in depth, were collected every 3 days. Distilled water was supplemented from the top of column after collecting leachate. Methane concentration in leachate was determined by gas chromatograph equipped with FID (GC-14APF, Shimadzu Co.).

RESULTS AND DISCUSSION

1) Effects of Rice Straw Application on the Amounts of CH_4 Leach-

ing (Experiment 1)

Figure 3-5 shows the time course of CH_4 content in 60 ml of leachate. In the treatment without RS, CH_4 content kept a very small level throughout 27 days incubation (<0.002 mg $\text{CH}_4\text{-C}/60$ ml). On the other hand, CH_4 was detected from the 3rd day of incubation in treatments with RS, and increased sharply. Methane contents in leachate were different by RS application level until 15th day. On 18th day CH_4 content in 0.6% RS treatment reached that in 1.0% RS treatment, and then they showed plateau. So their CH_4 contents were considered to be at the saturation level on 18th day. They kept that level afterward. From the solubility of CH_4 at 25°C , the equilibrium pressure of CH_4 of 0.6% RS treatment in 18-24th days was estimated to be 0.84-0.91 atm. The finding that bubbles and cracks developed many in both treatments after 18th day corresponded well to the saturation date of CH_4 . On the contrary, the CH_4 content in leachate increased steadily until 27th day in 0.3% RS treatment.

Total amounts of percolated CH_4 during 27 days incubation were 1.9, 4.4 and 4.8 mg in the treatments with 0.3, 0.6 and 1.0% RS, respectively. ITO AND IIMURA (1989) measured the amounts of CH_4 produced from Japanese paddy field applied with rice straw during one crop season. The percentage of carbon transformed into CH_4 was calculated to be ca. 9, 14, and 19% of that in original rice straw in the plots with 3, 6 and 10 t/ha of RS application (depth of plow layer: 10 cm), respectively. Their RS application level was in correspondence with 0.3, 0.6 or 1.0% of RS applied in this experiment. Based on their data, the amounts of CH_4 percolated for 27 days incubation in the present experiment were estimated to be ca. 6, 5 and 2% of CH_4 produced from 0.3, 0.6 and 1.0% RS, respectively. The lower percentage of percolated CH_4 against total produced CH_4 in treatments with higher amount of RS application was due to the saturation of CH_4 in leachate.

2) Effects of Percolation Rate on the Leaching of CH_4 (Experiment 2)

Figure 3-7 shows the time course of total CH_4 content in leachate with different percolation rate. Irrespective of percolation rate, CH_4 content increased from 6th day of incubation, and reached the saturation level around 15th or 18th day. So the amount of percolated CH_4 in the treatment with 0.52 cm/day percolation rate was double as much as that with 0.26 cm/day, and that with 1.0 cm/day was again double of that with 0.52 cm/day. The time course of CH_4 contents were similar in pattern each others.

YAGI ET AL (1990) reported that CH_4 flux to the atmosphere was reduced by percolation. They considered that the decrease of CH_4 flux was due to the introduction of oxygen into submerged soil with percolating water and resultant increase of soil Eh. On the other hand, it is known that percolation stimulates microbial activities by eliminating toxic substances produced by microorganisms under the submerged condition, especially in the soil rich in easily decomposable organic materials (TAKAI ET AL 1974). The result of present experiment indicated that different percolation rate had no effect on the CH_4 concentration in leachate. The total amount of CH_4 in leachate during 30 days in the treatments with 0.26, 0.53 and 1.0 cm/day percolation rates

corresponded to 3, 7 and 15% of CH_4 produced from rice straw in one crop season, respectively. Thus further amounts of CH_4 may be percolated down by increasing the percolation rate.

3. CH_4 OXIDATION IN SUBSOIL

Oxidation of CH_4 and total water soluble organic carbon (TOC) in subsoil, which was percolated from plow layer, was investigated by column experiment.

It is known that Fe^{2+} ion percolated into subsoil is immediately oxidized to ferric hydroxide in Brown Lowland soils (MATSU-MOTO ET AL 1971).

The oxidation process of Fe^{2+} iron in the subsoil inspired us to conduct the experiment on the CH_4 oxidation in subsoil. In this study, we investigated CH_4 oxidation in subsoil and the contribution of ferric iron reduction coupled with CH_4 oxidation to total ferric iron reduction in subsoil (MIURA ET AL 1992b).

MATERIALS AND METHODS

Three hundred grams of plow layer soil (Typic Haploaquept) was mixed with pulverized rice straw (0.6% w/w), packed into a glass column (diameter: 7 cm, height: 12 cm), and then submerged (25 C). Fifty grams of subsoil was packed in a small glass column (diameter 3 cm, height: 10 cm) and then submerged as well.

Four treatments were prepared as follows (Fig. 3-9).

treatment 1: plow layer soil only

treatment 2: subsoil only

treatment 3: subsoil connected to plow layer soil

treatment 4: two subsoils connected to plow layer soil

In treatments 3 and 4, air between columns was expelled completely with water. Sixty ml of leachate was collected every 3 days from the outlet of column without any exposure to the atmosphere.

RESULTS AND DISCUSSION

Fig. 3-10 shows the time course of CH_4 content in leachate. In the treatment of plow layer soil only (treatment 1), CH_4 was detected from day 3. Its content increased steeply from day 6 and reached the saturation level on day 15. Methane was scarcely detected throughout 30 days ($< 0.02 \text{ ug/ml}$) in the treatment of subsoil only (treatment 2). In the treatment of subsoil connected to plow layer soil (treatment 3), CH_4 content in leachate was very low during first 12 days, and then it increased gradually till day 30. In case of the treatment extra subsoil column was connected (treatment 4), CH_4 content was low until day 18, then increased gradually as the case of treatment 3.

From the above results, it was known that CH_4 in leachate decreased in concentration by percolating the subsoil, but that the reduction became small in the latter half of incubation period. The connection of additional subsoil to treatment 3, decreased only small amount of CH_4 in leachate, as shown in treatment 4.

4. CH_4 FLUX DISTRIBUTION TO THE ATMOSPHERE AND TO SUBSOIL

Methane fluxes from paddy fields are now paid special attention in relation to greenhouse effect. But the flux to the atmosphere is not the sole flux direction of CH_4 produced in paddy soils. Pot experiment growing rice plant was conducted to elucidate the effects of percolation rate and of rice straw

application on the CH_4 fluxes both to the atmosphere and to subsoil. The amount of CH_4 carbon percolated to subsoil was evaluated in comparison with other organic carbon in leachate (MURASE ET AL 1992).

MATERIALS AND METHODS

Three kilograms of Anjo Yellow Soil (Dystrochrept) with basal fertilizers were put in pot with 18 g of chopped rice straw (RS-treatment), submerged and then transplanted with two rice seedlings. Planted and non-planted pots with chemical fertilizer only (CF-treatment) and non-planted pots with rice straw were also prepared for 5 mm/day percolation treatment (Table 3-4).

During cultivation, pots were percolated every 2 days with amounts of 0, 200 and 600 ml, which corresponded to 0, 5, and 15 mm/day of percolation, respectively. Leachate was collected every 6 days with a 50-ml syringe via the glass tube installed to the outlet of pot without any exposure of leachate to the atmosphere. Methane concentration in leachate was determined with gas chromatograph with FID (KIMURA ET AL 1992b). Methane emission to the atmosphere was measured by the closed chamber method (KIMURA ET AL 1991b).

RESULTS AND DISCUSSION

1) Chemical Fertilizer Treatment (CF-Treatment)

Methane emission to the atmosphere and to subsoil from each treatment was shown in Fig. 3-13 with six day mean temperature of daily mean temperature. Methane emission to the atmosphere from planted CF-treatment was low until July 20 (Fig. 3-13a). The peaks were observed twice on August 1 (though weak) and August 19. Similar two peaks were observed by YAGI AND MINAMI (1990b) in the middle of July and the middle of August. Methane emission from non-planted CF-treatment was very low (< 0.2 mg-C/day) throughout cultivation period.

Methane leached from non-planted CF-treatment was detected from the first measurement on June 14 and reached a high level on August 7 (Fig. 3-13a). We regarded the level as the saturation level because the level was the ceiling and kept plateau. The partial pressure of equilibrated CH_4 in air phase (bubbles) was calculated to be 0.9 atm. Methane was also detected in the leachate of planted CF-treatment from June 14. But it kept lower level than non-planted treatment until September, while CH_4 emission to the atmosphere was very active in planted CF-treatment from the middle of July. This finding suggested that CH_4 produced in paddy soil was transferred preferentially to the atmosphere.

2) Rice Straw Applied Treatment (RS-Treatment)

Methane emission to the atmosphere from planted RS-treatments was detected 1 week after submergence (Fig. 3-13a). There were three peaks on July 2, August 1 and August 19. YAGI AND MINAMI (1990b) also observed three peaks of CH_4 emission in rice straw applied paddy fields. The latter two peaks were on the same days when planted CF-treatment recorded them. After August 7, the amounts of CH_4 emission to the atmosphere were similar between CF-treatment and RS-treatments. KIMURA ET AL (1991b) also observed only a small difference in CH_4 emission among planted CF-treatment, manure applied treatment and RS-treatment in the 1990 pot experiment with the same Anjo soil.

YAGI ET AL (1990) reported that water percolation (5 mm/day) significantly reduced CH_4 emission to the atmosphere from paddy soil. In this experiment, different percolation rates (0, 5, and 15 mm/day) did not affect CH_4 emission to the atmosphere throughout cultivation period (Fig. 3-13b), suggesting different effects of water percolation on CH_4 emission, as mentioned before.

Methane in leachate was detected in all RS-treatments except for treatment 3 (with no percolation) from the first measurement, and reached saturation levels after 12 days of transplanting. Methane in leachate maintained the saturation level in non-planted treatment afterwards. While leached CH_4 from planted RS-treatments decreased with the growth of rice plants, suggesting active CH_4 transfer through rice plants at early growth stage. Leached CH_4 from planted RS-treatments kept unsaturated lower levels until September as was observed in CF-treatments.

There was no difference in CH_4 concentration of leachate between CF- and RS-treatments from July 26 under planted condition, and from August 7 under non-planted condition, respectively (Fig. 3-13a). Methane concentration in leachate from the treatment with 15 mm/day percolation rate was higher than 5 mm/day treatment except for 2 sampling times in the beginning of July, suggesting the acceleration of CH_4 production with higher percolation.

3) Total Amounts of CH_4 Fluxes

Total amounts of CH_4 fluxes were shown in Table 3-5. There was no difference in CH_4 emitted to the atmosphere among the planted treatments with different percolation rates, while CH_4 concentration in leachate from planted 15 mm/day RS-treatment was higher than 5 mm/day RS-treatment and the total amounts of CH_4 leached was more than three times higher in the former treatment (251.2 mg-C) than in the latter treatment (71.0 mg-C). This result suggested that CH_4 production in submerged soil was accelerated with higher percolation rate.

Cumulative CH_4 fluxes were divided into early and late stages at the end of July, when rice plant reached the panicle initiation stage (Table 3-5). It was known that the physiological properties of rice plant induce its rhizosphere environment reductive from around this stage (KIMURA ET AL 1982). In planted RS-treatments, nearly equal amounts of CH_4 were fluxed to the atmosphere in both stages, while the dominant stage was in the late stage in planted CF-treatment with 83% of the total. The amount of CH_4 emitted to the atmosphere from planted CF-treatment in the late stage was close to those from planted RS-treatments in that stage. Methane fluxes to subsoil was more biased to the late stage: 94-95% of the total in CF-treatments and 58-60% in RS-treatments irrespective of planting and percolation rate. In addition, the amounts of CH_4 fluxes to subsoil in the late stage were almost same between CF- and RS-treatments with 5 mm/day percolation irrespective of plant growth (Table 3-5). Total CH_4 fluxes to subsoil accounted for 2.4-8.6% of the sum of emitted and leached CH_4 in planted treatments and 76-92% in non-planted treatments, respectively.

5. ESTIMATION OF CH_4 IN GROUND WATER RELEASING ALONG THE AGRICULTURAL USE

The CH_4 produced in the plow layer of paddy fields is known not only to be emitted to the atmosphere, but also to be leached downwards with percolation water (KIMURA ET AL 1992b, MURASE ET AL 1992). Although some portion of leached CH_4 is decomposed in subsoil (MIURA ET AL 1992b), there remains a possibility of the other portion to be carried into ground water. It has already been known that ground water is contaminated with N_2O , another greenhouse gas.

In this section, the CH_4 contents in ground water using for irrigation were surveyed in Aichi Prefecture, Central Japan, and the amounts of CH_4 releasing along the use of ground water for irrigation were estimated in comparison with the amounts of CH_4 emission from paddy fields.

SAMPLES AND ANALYTICAL METHODS

Samples: One hundred and four samples of ground water using for irrigation were collected from 23 cities, towns and villages in Aichi Prefecture, Central Japan. Sampling sites were shown in Fig. 3-7.

Sampling Method: Newly pumped-up ground water was collected with a syringe. In case pumping-up facilities are not available, ground water was directly collected with a water sampler throwing it into a well.

RESULTS AND DISCUSSION

CH_4 was detected ($>0.008 \text{ g/m}^3$) from 49 of the total 104 samples (47% of the total). The average CH_4 content in CH_4 detected samples was 1.92 g/m^3 . The average content of CH_4 in all samples was 0.90 g/m^3 . Based on the amounts of ground water using in agricultural sector in Aichi Pref. in 1990 and the average content of CH_4 obtained here, the amount of CH_4 released to the atmosphere using the ground water in agricultural sector was estimated to be 21.7 ton/yr.

According to the estimation of Kimura et al (1991a) on CH_4 production in paddy field derived from soil organic matter, the total CH_4 production from paddy fields in the areas surveyed was estimated to be 1.9-2.0 ton/one crop season. So the amount of CH_4 released along the irrigation of ground water corresponded to ca. 1% of the total CH_4 production through the decomposition of soil organic matter. As the CH_4 emission from paddy fields is usually 5 to 10 times larger in amounts than the above estimated CH_4 production (Part I in this report), the contribution of ground water irrigation to the total CH_4 fluxes to the atmosphere from agricultural sector is further low. On the other hand, as the amount of ground water using in agricultural sector is less than 10% of the total use of ground water, mainly in industrial sector, the total CH_4 released due to the use of ground water is considered to be a few percentages of the CH_4 emission from paddy fields.

CH_4 contents in ground water were greatly fluctuated among Areas as shown in Table 3-4. Generally, CH_4 contents were larger in the area of river mouth than in the area of upper stream. For example, CH_4 was not detected in all 12 samples in Area 2, while CH_4 was detected with the highest proportion and the largest average content of 3.45 g/m^3 in Area 1. The depth of well and soil texture were also the important factors for CH_4 contents in ground water. At Atsumi area, where soil texture is dominantly

sandy to stony and the depth of wells are less than 10 m, CH₄ was detected only from 3 of 16 samples and their average CH₄ content, 0.046 g/m³, was 1/20 of the total average. The amount of CH₄ releasing along the irrigation of ground water in Area 1 was estimated to be 25,200 kg/yr. In this area, the depth of wells are in general deeper than 100 m and soil texture was dominantly silty to light clayey. In addition, the pumping-up amount of ground water for irrigation was far larger than those of the other areas.

From these results, soil texture around sampling sites was considered to be one of the important factors determining the CH₄ content in ground water. Fig. 3-8 shows the relationships between CH₄ contents in ground water and soil texture at sampling sites. The percentage of ground water samples from which CH₄ was detected was only 20% where soil texture was sandy, while CH₄ was detected with higher frequency of 60% in silty soils. The proportion of samples which contained larger amounts of CH₄ was also higher in finer texture soils. Another important factor fluctuating CH₄ contents was the depth of wells. Fig. 3-9 clearly shows that the deeper the depth of wells, the higher the percentage of CH₄ detection and the higher the proportion of samples with larger CH₄ contents.

The relationships between CH₄ contents and physicochemical properties of ground water including pH, R_pH (pH after excluding CO₂), EC and contents of inorganic-P, NH₄-N, NO₃-N, Cl, SO₄, Na, K, Ca, Mg, Fe, Mn, Zn, Cu, Si and B were also investigated. Neither physicochemical properties nor the contents of inorganic constituents correlated with the CH₄ content in ground water. However, their distribution patterns of measured values were different between the CH₄ detected and non-detected ground water samples. Samples containing CH₄ distributed their Eh in lower Eh range than those without CH₄ (Fig. 3-10). Especially, when Eh of ground water was lower than 100 mV, CH₄ was detected in all 6 samples. Since all Eh values were higher than 30 mV, CH₄ in every ground water investigated was considered to be produced somewhere else and to be brought into ground water. COD, Fe, Mn, NH₄-N and NO₃-N contents were known to influence the CH₄ detection.

The discriminant analysis of CH₄ detection was conducted with the above physicochemical properties and inorganic constituents as variables. Eh, NO₃-N and COD were found to be significant variables at the significant level of 15%, and CH₄ detection was estimated from the following equation;

$$Y = -1.476 \times 10^{-2} \text{Eh(mV)} - 1.436 \times 10^{-2} \text{NO}_3\text{-N(mg/L)} + 2.454 \times 10^{-1} \text{COD(mg/L)} + 4.697$$

In case Y is positive, CH₄ is expected to be detectable.

F values of these three factors were 66.59 for Eh, 6.90 for NO₃-N and 2.77 for COD, respectively. It is expected from this equation whether CH₄ is detected or not with 14.7% of apparent error rate.

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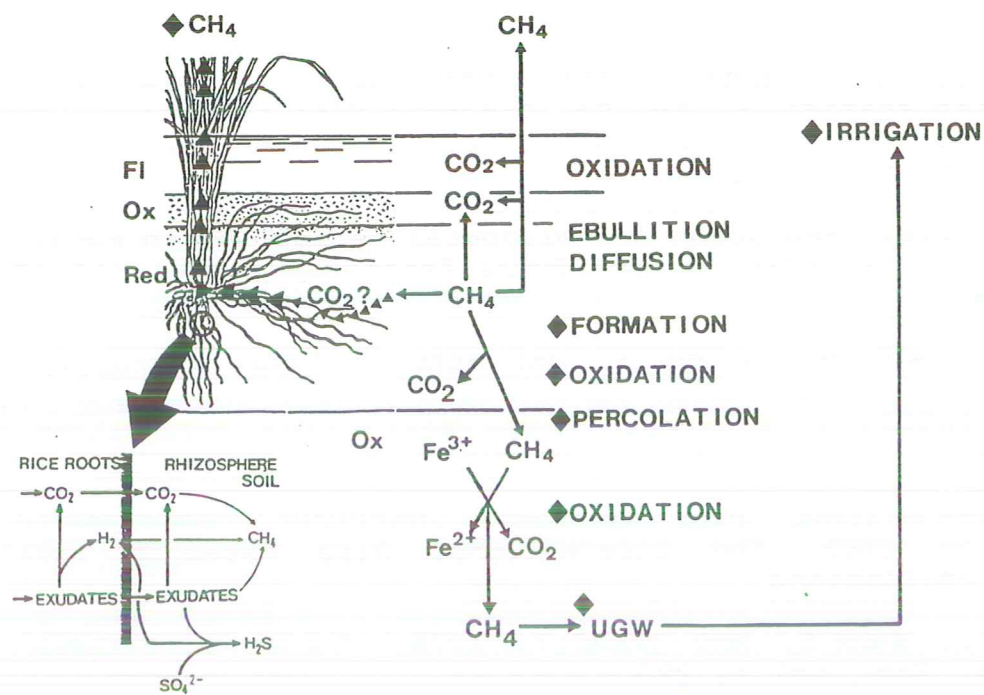


Fig. 1. Fates of Methane in Paddy Field

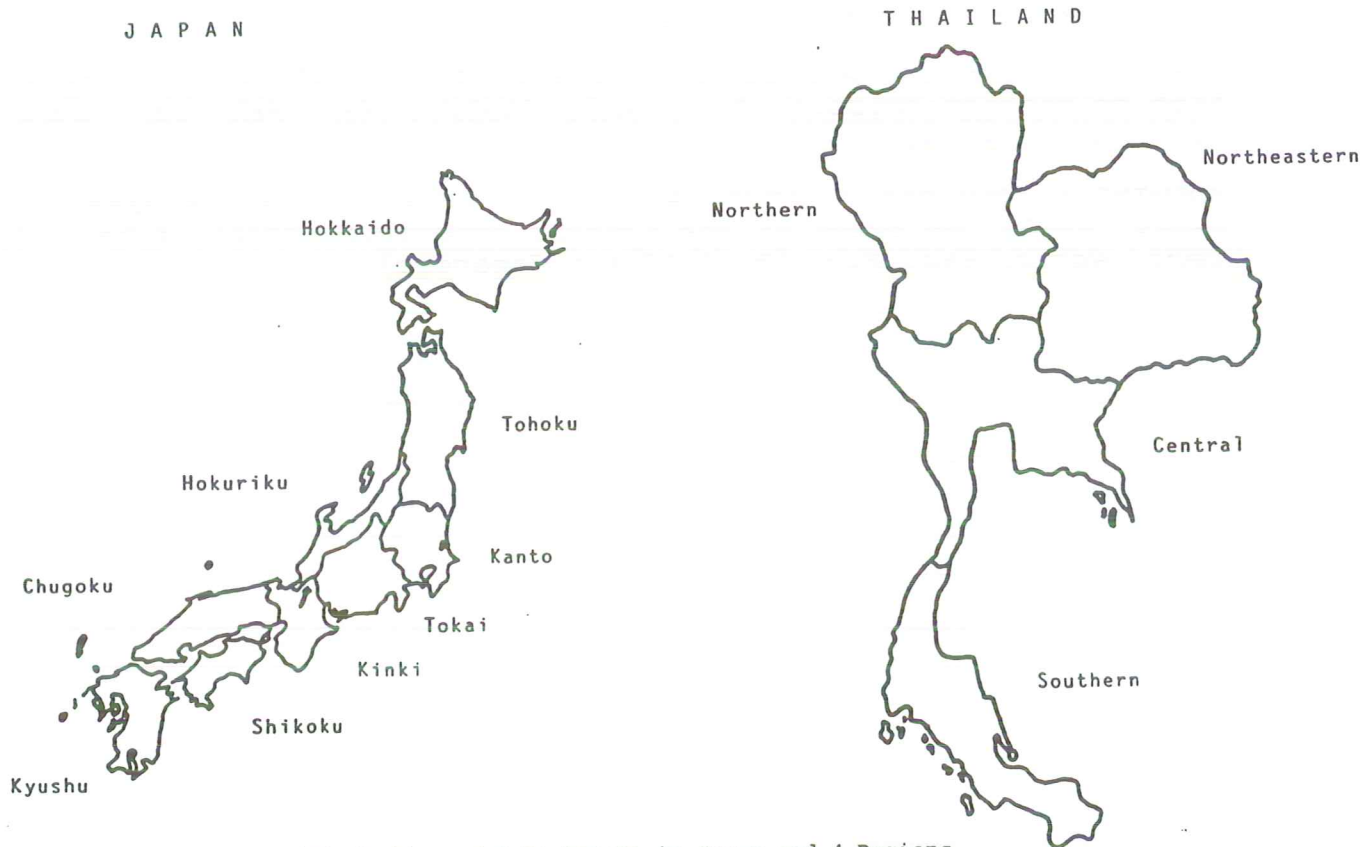


Fig.1-1. Distribution of 8 Districts in Japan and 4 Regions in Thailand

Table 1-1. The Estimated Amount of Potential CO₂ Production from 15 Soil Series Groups in 7 Japanese Districts (ton-C)

Soil Series Groups	Tohoku	Kanto	Hokuriku	Chubu	Kinki	Chugoku Shikoku	Kyushu	Total
Sand-dune Regosol	0 ¹⁾	0	NE	0	0	0	0	0
	0 ²⁾	0	NE	0	0	0	0	0
Andosol	51,945	0	0	0	NE	0	1,428	53,373
	43,189	0	0	0	NE	0	1,482	44,671
Wet Andosol	150,198	221,951	33,103	21,876	NE	39,126	80,339	546,594
	140,441	213,636	32,610	22,409	NE	39,899	83,361	532,356
Gleyed Andosol	17,480	37,413	NE	8,906	0	6,976	1,912	72,687
	16,396	36,154	NE	9,144	0	7,159	1,985	70,838
Brown Forest S.	NE	NE	0	0	0	0	0	0
	NE	NE	0	0	0	0	0	0
Gray Upland S.	7,999	6,303	NE	6,408	4,698	26,547	16,110	68,065
	7,694	5,930	NE	6,535	4,953	27,095	16,754	68,961
Gleyed Upland S.	12,290	1,596	NE	1,423	NE	16,596	2,071	33,976
	11,387	1,442	NE	1,453	NE	17,038	2,157	33,477
Red Soil	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
Yellow Soil	23,785	11,753	11,524	31,898	18,846	46,584	55,871	200,261
	22,320	11,060	11,346	32,580	19,841	47,572	57,896	202,615
Dark-red Soil	0	0	0	0	NE	0	2,431	2,431
	0	0	0	0	NE	0	2,517	2,517
Brown Lowland S.	45,223	12,307	4,059	1,592	16,261	23,935	38,953	142,330
	41,988	11,726	3,996	1,637	17,088	24,415	40,260	141,110
Gray Lowland S.	216,350	228,426	95,899	106,154	169,161	247,637	212,701	1,276,328
	199,885	219,001	94,430	108,604	175,793	252,165	220,009	1,269,887
Gley Soil	207,715	166,272	183,698	70,195	78,737	98,591	88,038	893,247
	187,910	157,274	180,803	71,808	80,853	100,431	91,244	870,323
Muck Soil	55,694	33,829	2,051	1,428	NE	2,399	7,255	102,657
	51,031	31,873	2,020	1,457	NE	2,411	7,497	96,289
Peat Soil	28,722	17,339	NE	1,002	NE	49	938	48,049
	26,557	16,581	NE	1,027	NE	50	974	45,189
Total	817,400	737,188	330,334	250,883	287,704	508,440	508,048	3,439,998
	748,798	704,677	325,205	256,654	298,528	518,235	526,136	3,378,233

NE : Due to the lack of data, they could not be estimated.

1) Upper row : The amount of gas production when n=0.7

2) Lower row : The amount of gas production when n=1

Table 1-2. The Estimated Amount of Potential CH₄ Production from 15 Soil Series Groups in 7 Japanese Districts (ton-C)

Soil Series Groups	Tohoku	Kanto	Hokuriku	Chubu	Kinki	Chugoku Shikoku	Kyushu	Total
Sand-dune Regosol	0 ¹⁾	0	NE	0	0	0	0	0
	0 ²⁾	0	NE	0	0	0	0	0
Andosol	1,076	0	0	0	NE	0	70	1,147
	760	0	0	0	NE	0	75	835
Wet Andosol	2,860	7,009	851	696	NE	2,156	3,072	16,644
	2,515	6,525	828	726	NE	2,226	3,269	16,089
Gleyed Andosol	320	1,416	NE	278	0	338	26	2,378
	280	1,339	NE	292	0	353	28	2,292
Brown Forest S.	NE	NE	0	0	0	0	0	0
	NE	NE	0	0	0	0	0	0
Gray Upland S.	149	163	NE	166	119	914	292	1,803
	139	147	NE	172	131	951	315	1,855
Gleyed Upland S.	162	32	NE	34	NE	359	15	602
	141	27	NE	35	NE	379	16	598
Red Soil	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
Yellow Soil	270	88	279	764	438	1,285	1,211	4,334
	236	77	271	792	480	1,337	1,289	4,482
Dark-red Soil	0	0	0	0	NE	0	30	30
	0	0	0	0	NE	0	32	32
Brown Lowland S.	869	350	97	68	499	856	1,328	4,066
	755	318	94	71	545	888	1,405	4,076
Gray Lowland S.	4,173	5,341	2,533	3,338	4,926	9,088	5,849	35,249
	3,624	4,931	2,467	3,477	5,296	9,379	6,201	35,375
Gley Soil	3,105	2,564	3,706	1,517	1,723	2,400	2,032	17,049
	2,596	2,318	3,596	1,581	1,831	2,487	2,168	16,577
Muck Soil	1,052	735	31	20	NE	65	212	2,115
	894	668	31	20	NE	65	226	1,904
Peat Soil	879	393	NE	24	NE	2	4	1,303
	762	361	NE	25	NE	2	5	1,155
Total	14,917	18,091	7,498	6,903	7,704	17,462	14,144	86,720
	12,702	16,711	7,287	7,191	8,283	18,067	15,029	85,270

NE : Due to the lack of data, they could not be estimated.

1) Upper row : The amount of gas production when n=0.7

2) Lower row : The amount of gas production when n=1

Table 1-3. The estimated amount of potential CO₂ and CH₄ production per unit area from various soils in 4 Thai Regions

REGION Soil Type	No of Soils	CO ₂ (ton-C/ha)		CH ₄ (kg-C/ha)	
		n=0.7	n=1.0	n=0.7	n=1.0
<u>CENTRAL PLAIN</u>					
Marine Alluvial	12	3.5	4.0	114	150
Brackish Water Alluvial	6	3.3	3.9	94	124
Fresh Water Alluvial	21	2.0	2.3	44	59
Low Humic Gley	13	2.3	2.6	55	73
Hydro. Gray Podzolic	1	0.5	0.6	7	10
Hydro. Non-calcic Brown	2	1.3	1.6	35	46
Grumusol	2	2.6	3.0	80	106
<u>NORTHEASTERN REGION</u>					
Fresh Water Alluvial	3	1.2	1.3	49	55
Low humic Gley	21	0.8	0.9	33	38
Hydromorphic Regosol	3	0.5	0.5	29	32
Hyro. Non-Calcic Brown	1	0.8	0.8	13	15
<u>NORTHERN REGION</u>					
Fresh Water Alluvial	8	1.4	1.6	41	47
Low Humic Gley	23	1.1	1.2	24	28
Humic Gley	2	0.7	0.7	6	7
Hydro. Gray Podzolic	1	1.5	1.6	135	150
<u>SOUTHERN REGION</u>					
Marine Alluvial	1	2.6	3.0	56	75
Brackish Water Alluvial	1	3.3	3.9	100	132
Fresh Water Alluvial	3	1.8	2.1	51	68
Low Humic Gley	14	1.4	1.6	40	52
Hydromorphic Regosol	3	1.2	1.4	52	67
Hydro. Gray Podzolic	2	1.2	1.4	40	53
<u>MEAN</u>					
WHOLE THAILAND	146	1.8	2.1	52	66
CENTRAL PLAIN	57	2.6	3.0	70	93
NORTHEASTERN REGION	28	0.8	0.9	34	38
NORTHERN REGION	34	1.2	1.3	30	35
SOUTHERN REGION	24	1.5	1.8	46	61

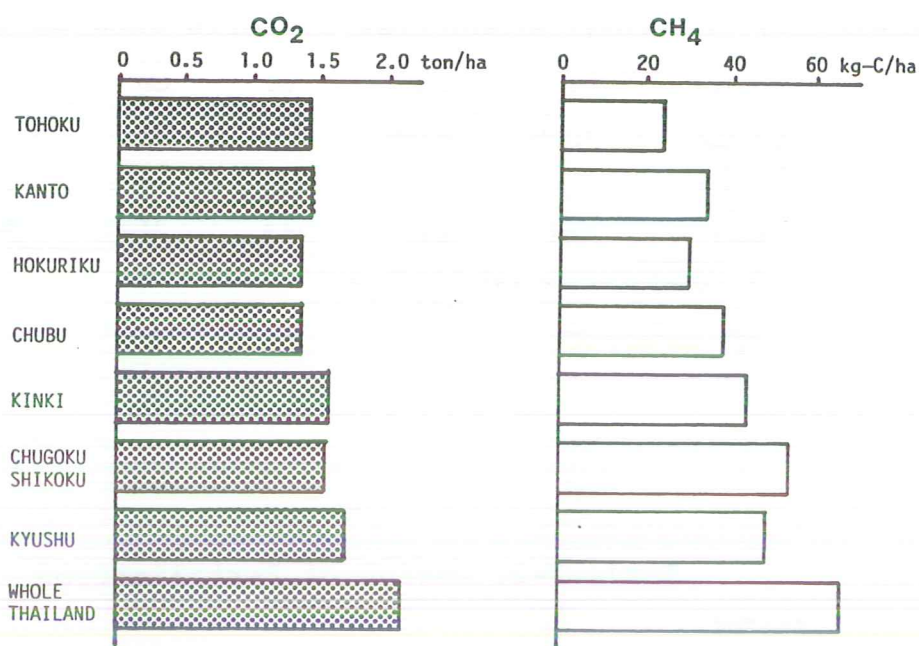


Fig. 1-2. The Estimated Amount of Potential CO₂ Production Per Unit Area in 7 Japanese Districts (ton-C/ha)

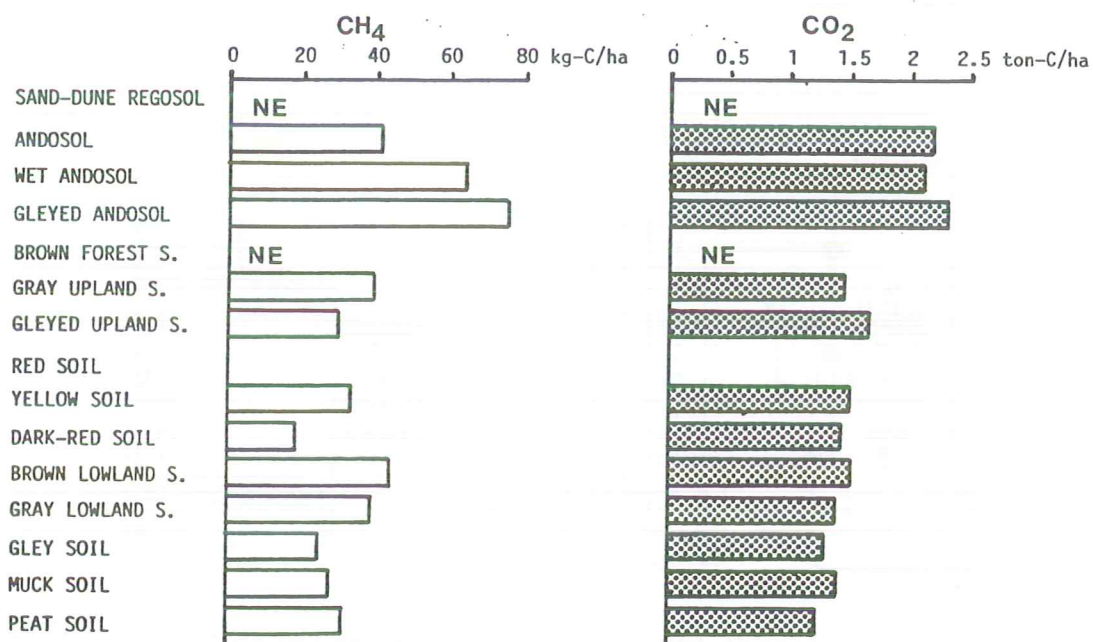


Fig. 1-3. The Estimated Amount of Potential CH₄ Production Per Unit Area from 15 Soil Series Groups (kg-C/ha)

Table 2-1. Chemical Properties of Soils Used in the Experiment

Soils	Total-C	Total-N	C/N	CEC*	pH(H ₂ O)	Texture
Anjo Soil	1.78 %	0.13 %	13.7	14.1	5.9	light clay
Fukushima						
Soil 1	1.28	0.11	12.0	14.0	6.1	light clay
Soil 2	1.66	0.11	14.8	14.0	6.6	light clay

Soil 1 : chemical fertilizer applied for 15 years

Soil 2 : 0.6 kg/m² rice straw applied for 15 years

* CEC : me/100 g soil

Table 2-2. Design of Fertilization

Anjo Soil

Plot 1 : No fertilizer

(without basal fertilizer nor top-dressed fertilizer)

Plot 2 : Chemical fertilizer*

Plot 3 : Chemical fertilizer* and cow dung manure**

Plot 4 : Chemical fertilizer* and rice straw***

Fukushima Soil

Soil 1 : Chemical fertilizer*

Soil 2 : Chemical fertilizer*

* : Basal : (NH₄)₂SO₄ 1.5 g, Calcium superphosphate 1.5 g, KCl 0.6 g.

Top-dressed : (NH₄)₂SO₄ 1.0 g twice

** : 40 g/pot (2 kg/m²) matured one (25%C, 3.1%N, C/N=8.1)

*** : 12 g/pot (0.6 kg/m²)

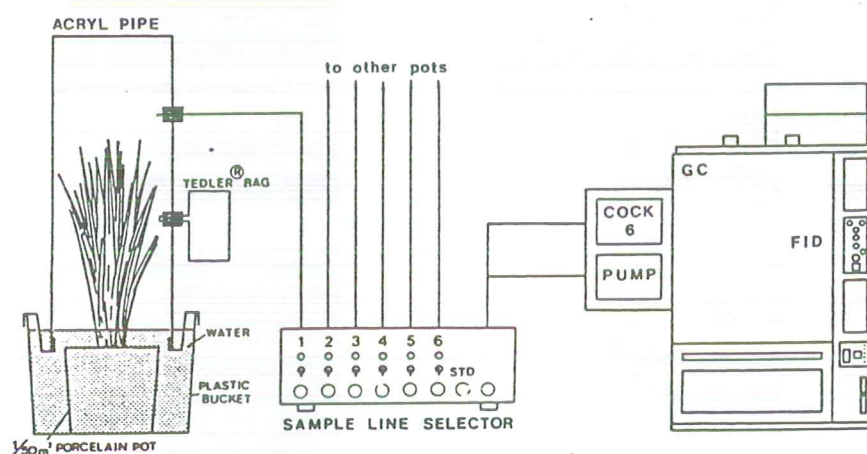


Fig.2-1. Layout of Assay System of Methane Emission from Paddy Soil

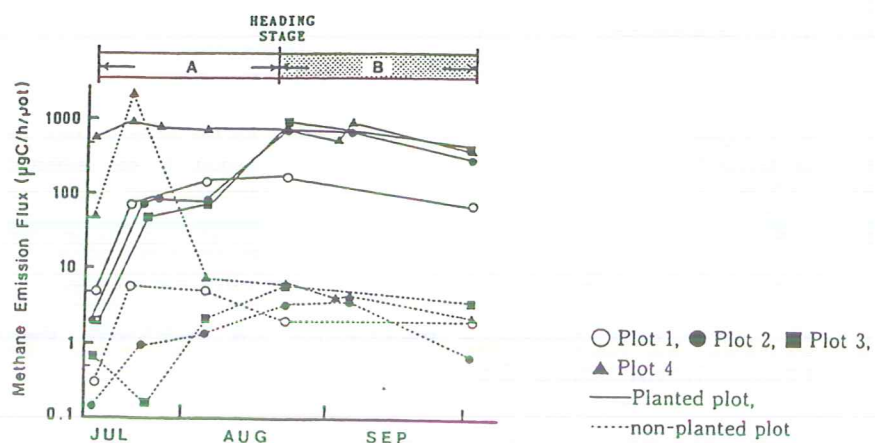


Fig.2-2. Seasonal Variation of Methane Emission (Anjo Soil)

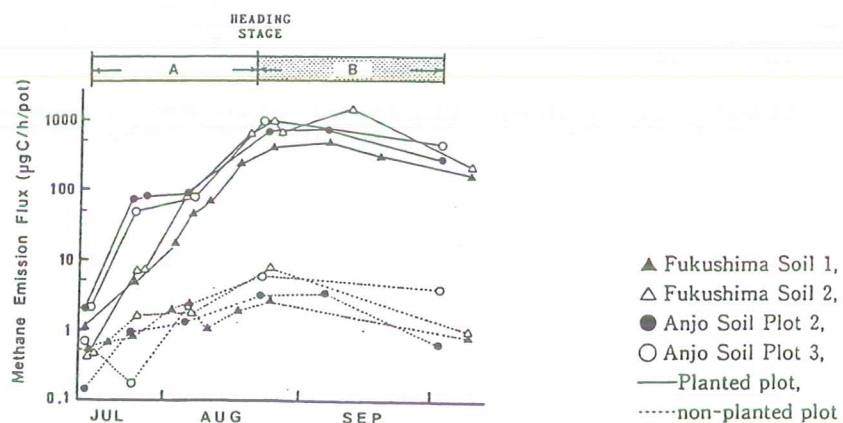


Fig.2-3. Seasonal Variation of Methane Emission (Fukushima Soil and Anjo Soil)

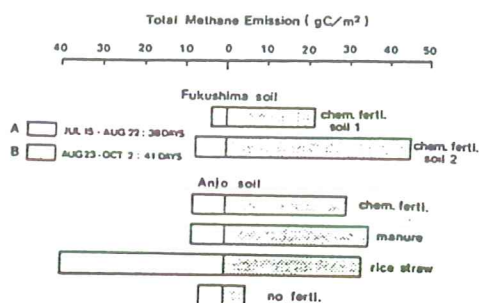
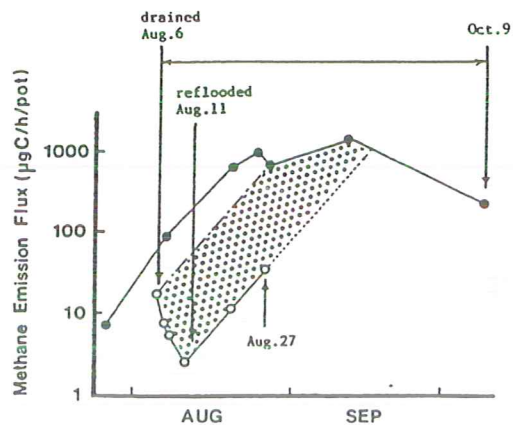


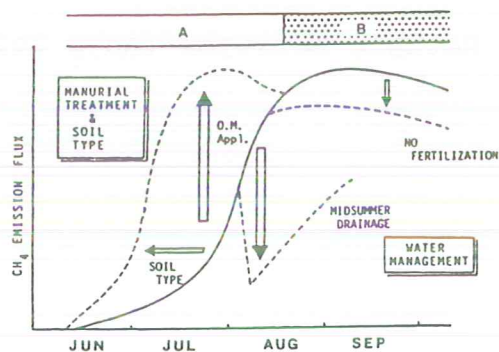
Fig.2-4. Total Methane Emission in the Early and Late Stages



○ Drained plot,
● Control (continuously flooded)
plot

Note : As the emission flux on August 6 was different between the plots, the shaded area was regarded as the area reduced by midsummer drainage.

Fig.2-5. Effect of Midsummer Drainage on Methane Emission (Fukushima Soil 2)



Note : A : the stage before head-
ing
B : the stage after head-
ing

Fig.2-6. Pattern of Methane Emission from Paddy Field and the Agricultural Practices Which Influence Its Emission

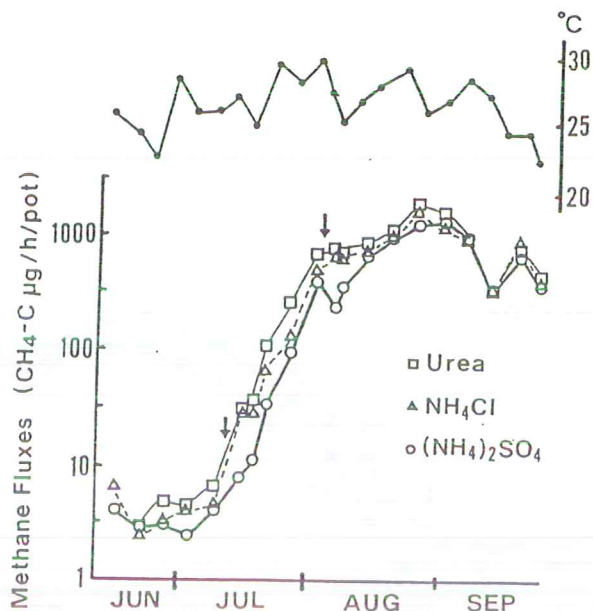


Fig.2-8 Five days mean temperature of daily mean temperature, and seasonal variation of methane fluxes to the atmosphere from paddy soils topdressed with three kinds of nitrogen fertilizer on their soil surface. Arrows indicate dates of topdressing.

TABLE 2-3. Total methane fluxes from paddy soil differently topdressed with nitrogen fertilizers. (mgCH₄-C/pot)

	(NH ₄) ₂ SO ₄	NH ₄ Cl	urea
broadcast	1,013(100 [*])	1,136(112)	1,320(130)
foliar spray	557(55)	451(45)	1,056(104)

From transplanting on 8 June 1991 to harvest on 25 Sept 1991 (109 days).

* Relative amounts of methane fluxes to (NH₄)₂SO₄ broadcast plot.

TABLE 2-4. Grain yield and number of ears differently topdressed with nitrogen fertilizers (per pot).

	(NH ₄) ₂ SO ₄		NH ₄ Cl		urea	
	grain	ears	grain	ears	grain	ears
broadcast	27.5g	21	24.9g	19	23.9g	18
foliar spray	21.0g	15	15.8g	14	21.4g	17

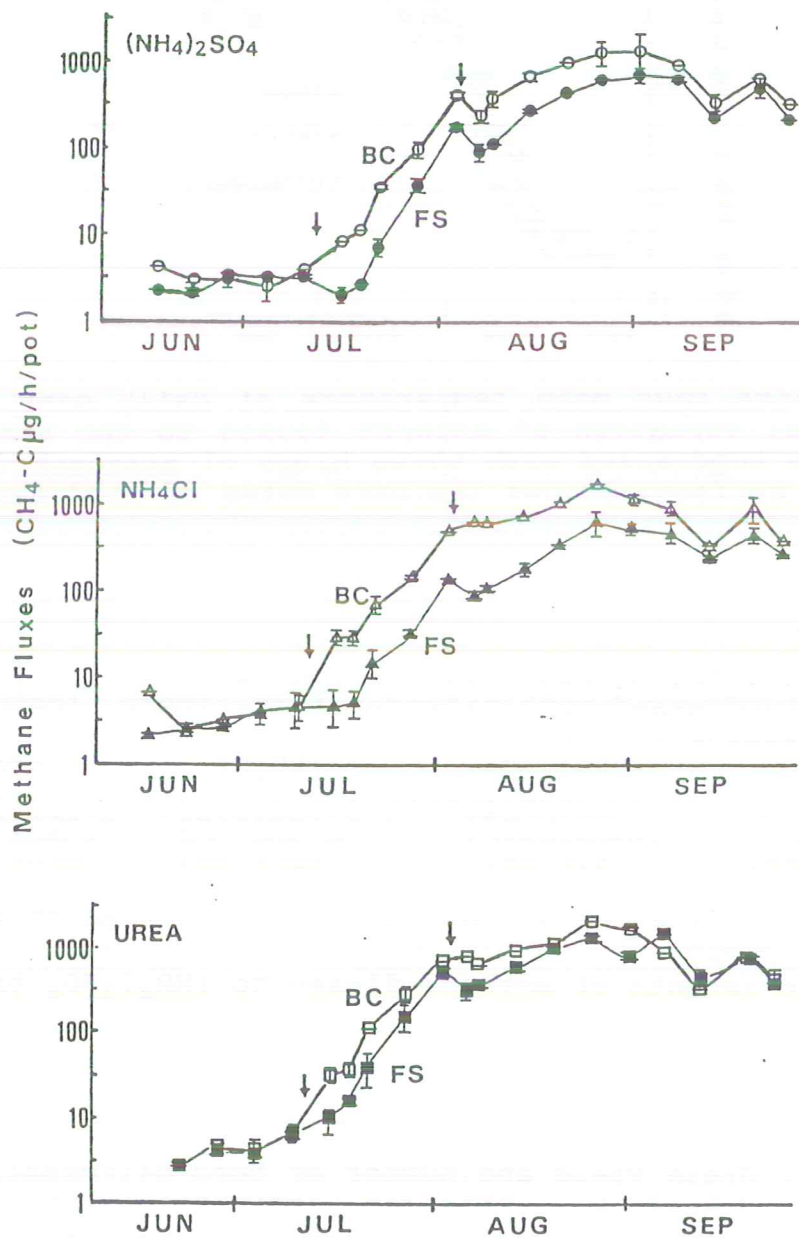


Fig.2-9 Effects of topdressing type of nitrogen fertilizers on methane fluxes from paddy soils. Arrows indicate dates of topdressing. BC:broadcasting. FS:foliar spray

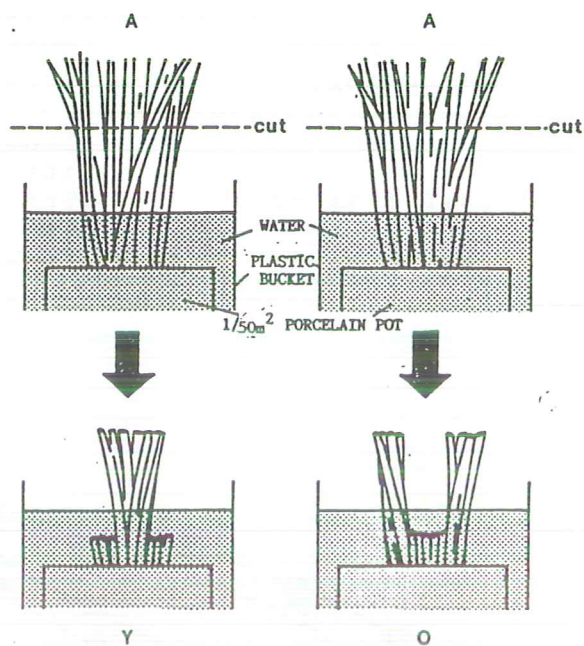


Fig. 2-10. Procedure of CH_4 Emission Measurement Through Old and Young Roots

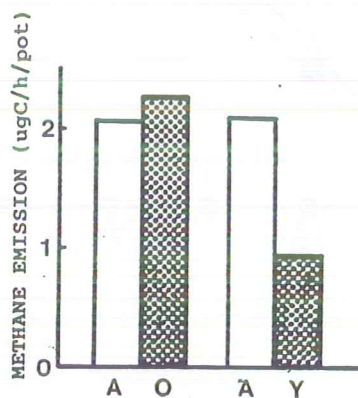


Fig. 2-11. Main Route of CH_4 Emission through Rice Plant
 A: All Stems above Water
 O: Old Stems above Water
 Y: Young Stems above Water
 (Excised Plant)

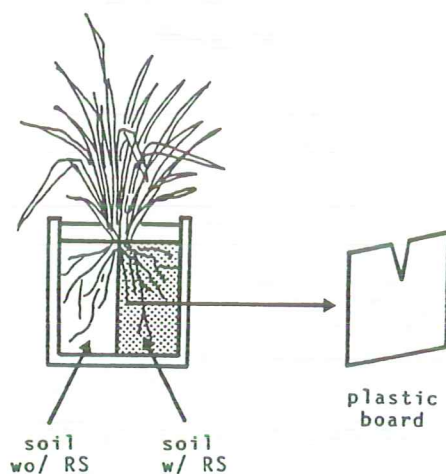


Fig. 2-12. Outline of Pot Preparation and Plant Growth

Table 3-1 Outline of Treatments

Treatment	Upper Layer (150g soil)	Lower Layer (150g Soil)
1	-	without RS
2	-	with 0.6% RS
3	with 0.3% RS	with 0.3% RS
4	without RS	with 0.6% RS
5	with 0.6% RS	without RS

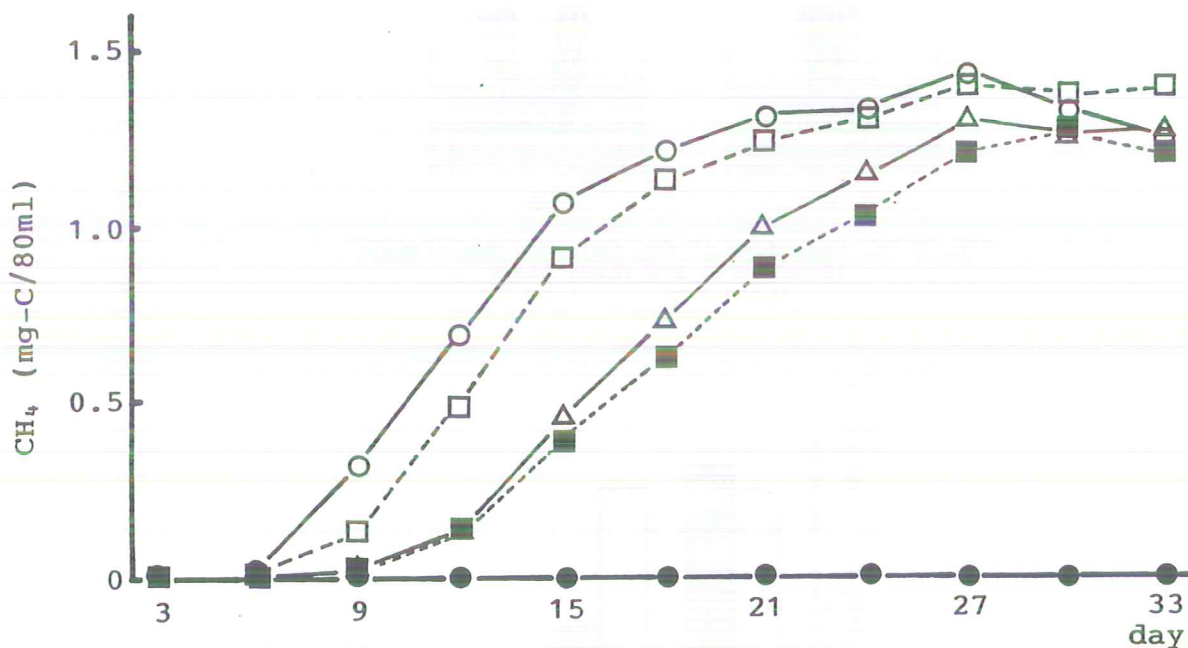


Fig. 3-1 Time Course of CH_4 Percolated into 80 ml Leachate
 Treatment 1:● Treatment 2:○ Treatment 3:△
 Treatment 4:□ Treatment 5:■

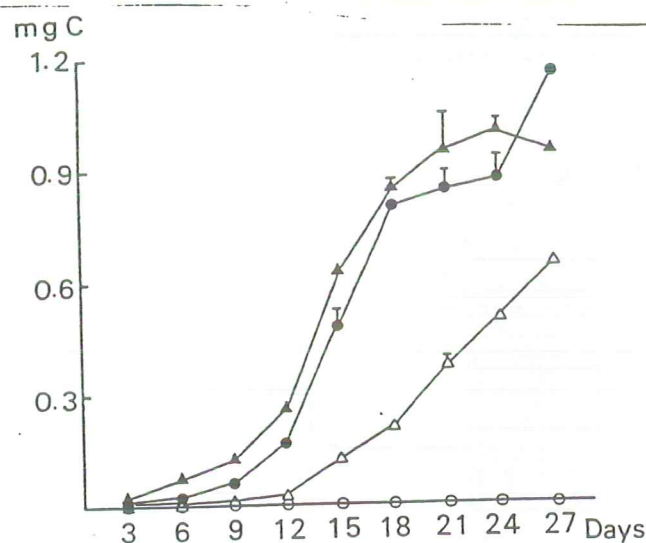


Fig. 3-2. Time Course of CH_4 Content in 60ml of Leachate
 Rice Straw: ○:0%, △:0.3%, ●:0.6%, ▲:1.0%

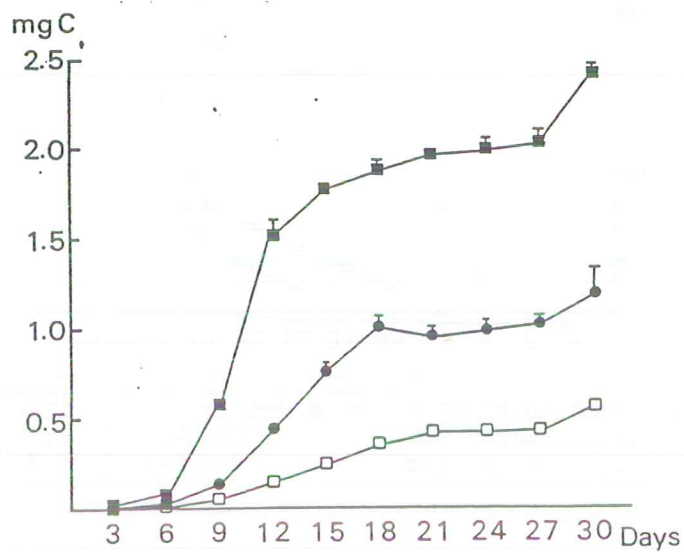


Fig. 3-3. Time Course of Total CH_4 Content in Leachate
Percolation Rate \square :0.26cm/day, \bullet :0.52cm/day, \blacksquare :1.0cm/day

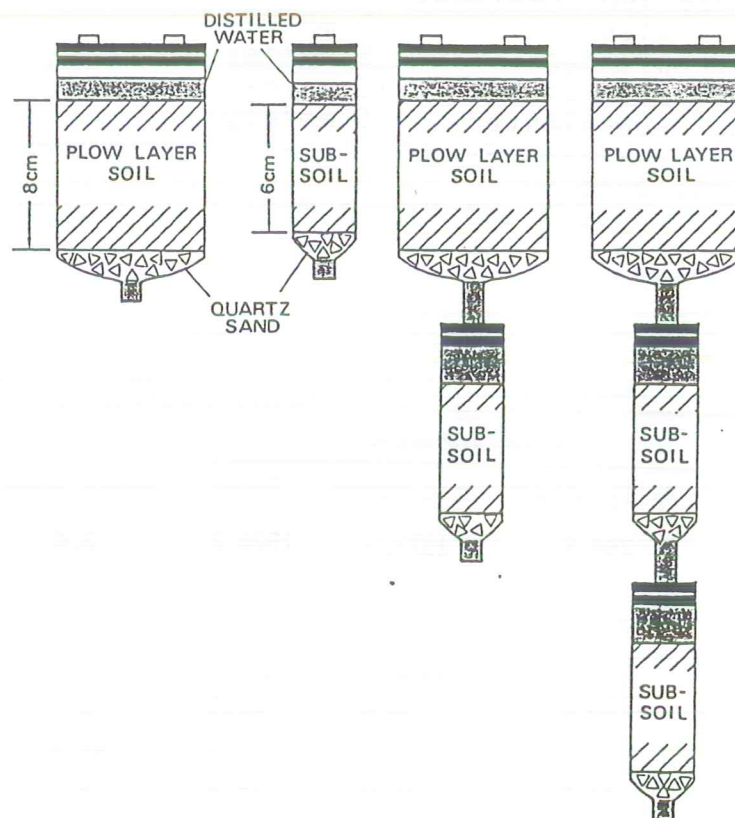


Fig. 3-4. Layout of Column Experiment

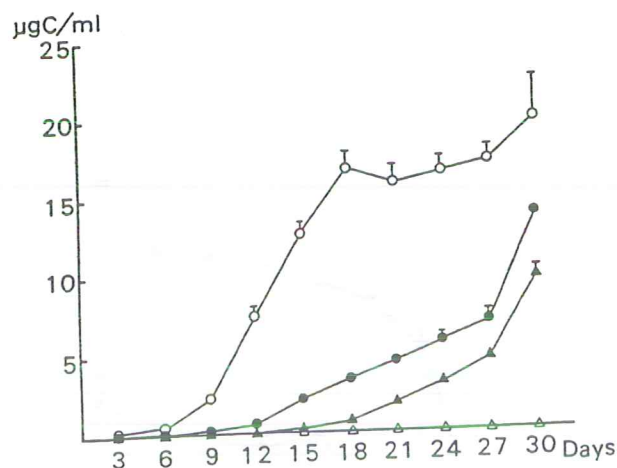


Fig. 3-5. Time Course of CH₄ Content in Leachate
 Treatment 1:○ Treatment 2:△
 Treatment 3:● Treatment 4:▲

Table 3-2. Outline of Treatments

Chemical Fertilizer Treatment (wo/Rice Straw; CF-Treatment)
 Treatment 1. planted 5 mm/day
 Treatment 2. non-planted 5 mm/day

Rice Straw Applied Treatment
 Treatment 3. planted 0 mm/day
 Treatment 4. planted 5 mm/day
 Treatment 5. planted 15 mm/day
 Treatment 6. non-planted 5 mm/day

Transplanting: June 8
 Topdressing: : July 9 and August 8

Table 3-3 Total amounts of CH₄ fluxes.(mg-C/pot)

Plots	To the atmosphere			To subsoil		
	Early stage*	Late stage*	Total	Early stage	Late stage	Total
CF-plots(5mm/day)						
planted	266.8	1327.5	1594.3	2.4	36.1	38.5
non-planted	1.6	5.4	7.0	3.7	73.1	76.8
RS-plots						
0mm/day						
planted	1123.7	1637.8	2761.5	0	0	0
non-planted	40.4	8.8	49.2	0	0	0
5mm/day						
planted	1080.1	1441.1	2521.2	29.7	41.3	71.0
non-planted	20.6	25.9	46.5	59.1	89.3	148.4
15mm/day						
planted	1210.6	1457.2	2667.8	99.6	151.6	251.2

*, Early stage: June 8- July 31 (54 days), Late stage: Aug. 1- Sep. 30 (61 days)

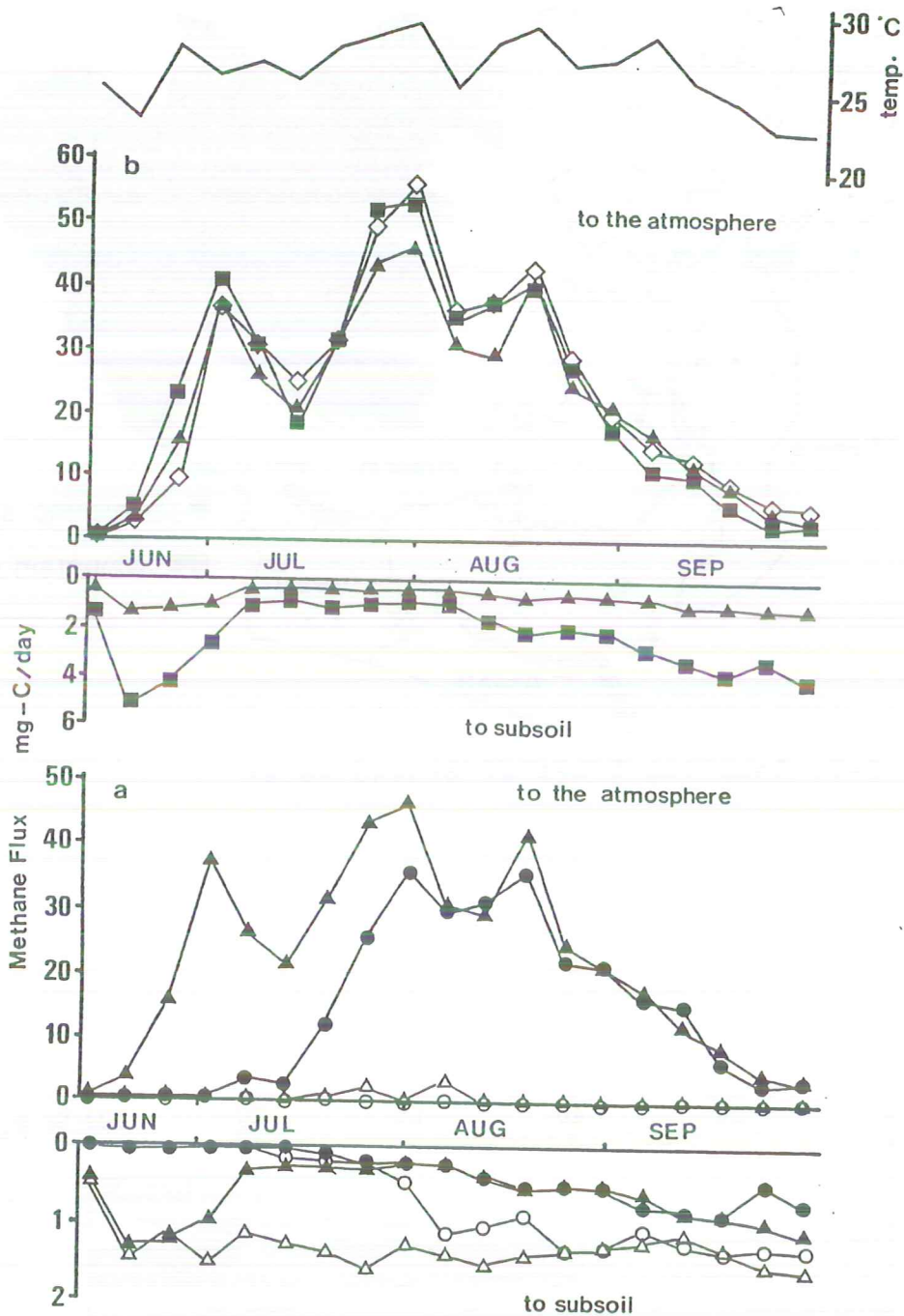


Fig. 3-6. Six Days Mean of Daily Mean Temperature and Seasonal Variation of CH_4 Emission to the Atmosphere and to Subsoil
 a: Effects of Rice Plant and Rice Straw Application on CH_4 Fluxes
 b: Effect of Percolation on CH_4 Fluxes (RS Treatment)
 Treatment 1: ● Treatment 2: ○ Treatment 3: ◇
 Treatment 4: ▲ Treatment 5: ■ Treatment 6: △

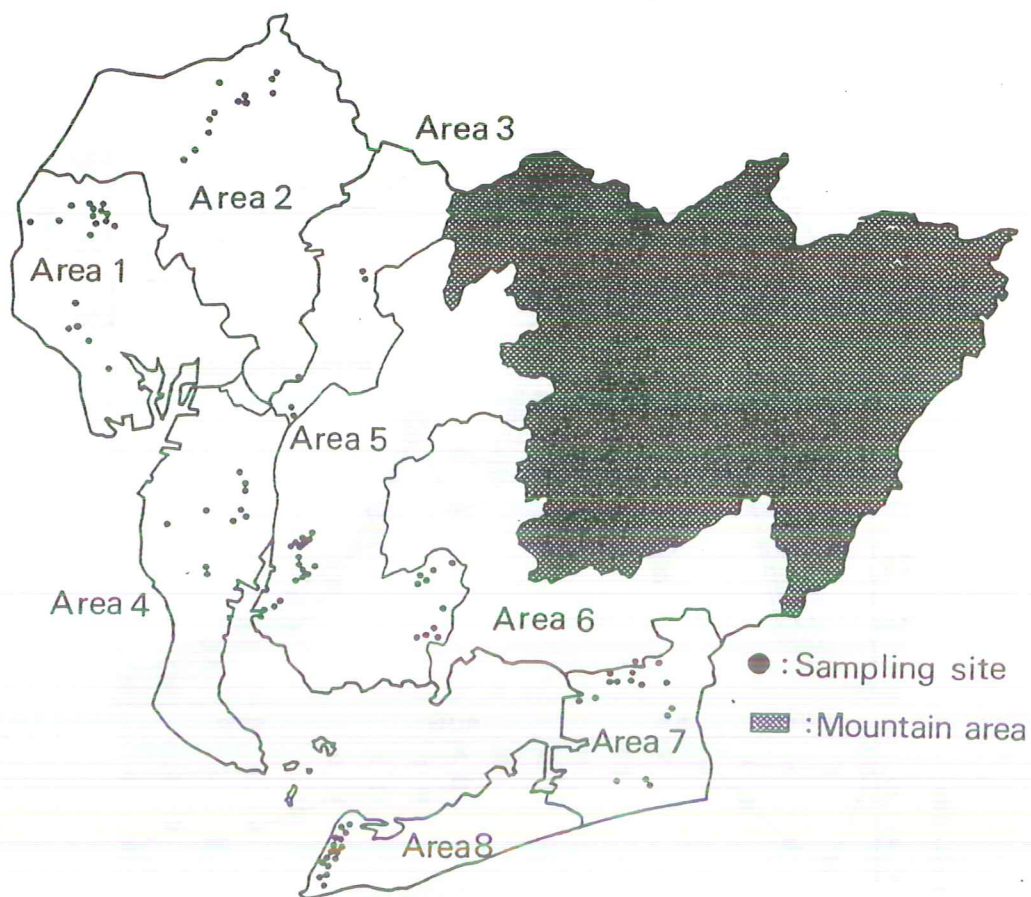


Fig. 3-7. Sampling Sites of Ground Water

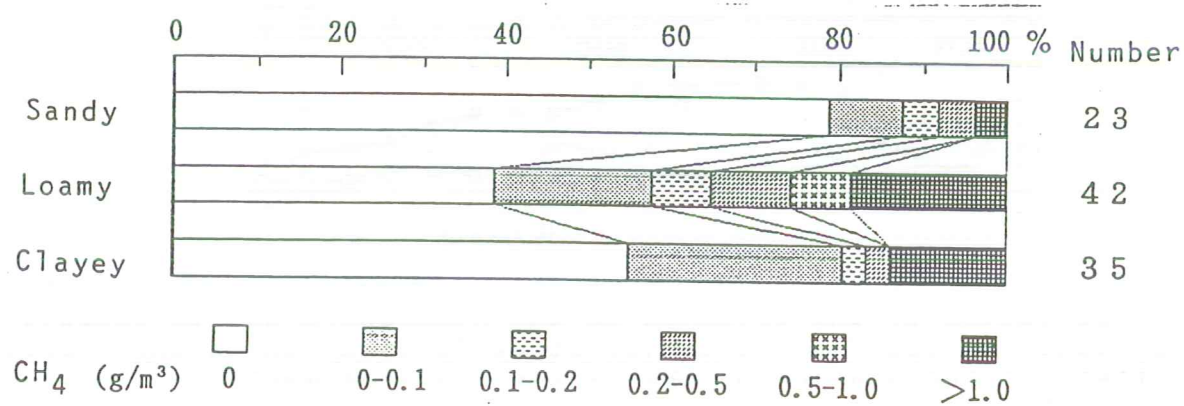


Fig. 3-8. Relationships between CH₄ Content in Ground Water and Soil Texture

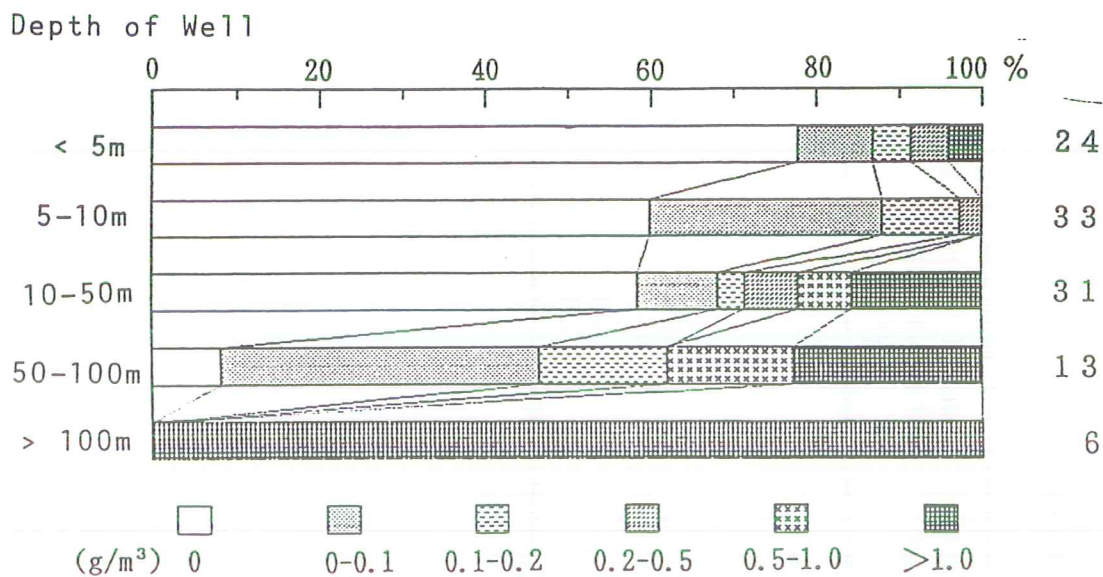


Fig. 3-9. Relationships between CH₄ Content in Ground Water and the Depth of Well

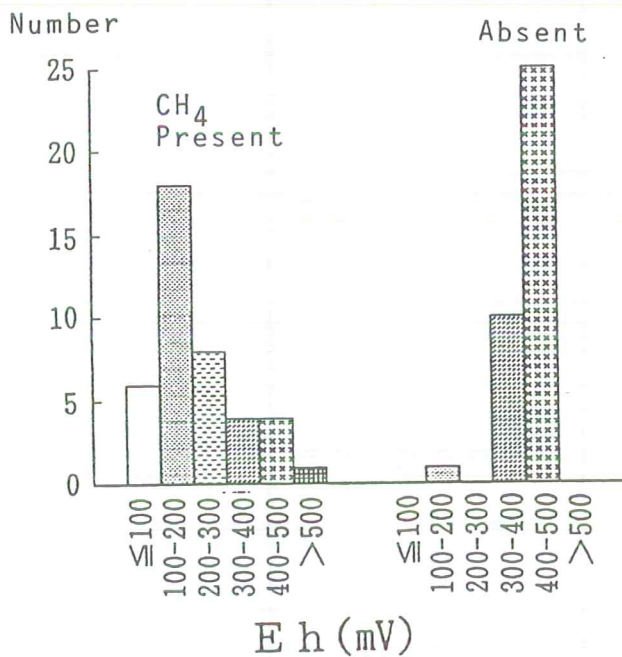


Fig. 3-10. Eh Variation of Ground Water and CH₄ Detection

Table 3-4. Average methane content and amount of methane releasing along irrigation of ground water in each Area.

Area	Number of samples	Number of CH ₄ detected samples	CH ₄ detection percentage (%)	Average CH ₄ content (g/m ³)	Amount of ground water used in agriculture (m ³ /day)	Amount of CH ₄ released from ground water (Kg/yr)
1	17	14	82	3.45	2011	25200
2	12	0	0	0	4625	0
3	5	3	60	0.041	437	7
4	10	7	70	0.203	1786	132
5	28	15	54	1.12	3767	1540
6	0	—	—	—	—	—
7	16	7	44	0.057	9713	201
8	16	3	19	0.046	16333	272

METHODOLOGY AND DATA USED TO ESTIMATE NATURAL N₂O EMISSIONS

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1 Introduction

Recent estimates of global soil N₂O emissions were all based on measured emissions from a limited number of ecosystems. These measurements were used as representative results for the global areas of each ecosystem, and the total emissions were calculated as emission x area. Such an approach does not consider the enormous spatial variability of fluxes reported by numerous authors (see Bouwman, 1990). A different approach involves stratification of ecosystems according to the major environmental parameters as proposed by Matson et al. (1989). This idea was elaborated in a global model to analyze the controls of N₂O emissions from soils. This global model will be discussed briefly here, with due attention to the use of soil data and derived information. More details on the model developed and the underlying principles of N₂O formation in soils for this study is described in detail in Bouwman et al. (1992a).

Five major regulators of N₂O production were considered in a simple soil model. A brief description of these regulators and their parameterization is presented here. The model structure is presented in the scheme of Figure 1. Three of these regulators vary monthly: effect of temperature on the decomposition of soil organic matter (SOD), effect of soil water availability (H₂O) and effect of oxygen limitation (O₂). The remaining two - soil fertility (FERT) and carbon and nitrogen availability (CARBON) - are constant through the year.

The relative importance of these factors was into non-dimensional indices, ranging from 0 to 10 or from 1 to 5, with high numbers signifying importance for N₂O production. Such translations may be simple for numeric data such as temperature. For control factors such as fertility, a subjective ranking of soil units was carried out. The suite of control indices were then combined to form indices for N₂O fluxes. Comparison of the scaled non-dimensional N₂O indices with field measurements of fluxes provides an evaluation of the overall behavior and logic of the model.

2 Databases used

The spatial resolution of the primary data sets used is 1° latitude by 1° longitude, ~110 km x 110 km at the equator. For these reasons, the model cannot resolve episodic effluxes of N₂O after rainstorms and localized "hot spots" which are often reported. The importance of such high-frequency, local events in the global budget has not been established. The model must parameterize their integrated effects and evaluate their contribution to the global annual flux. The primary gridded data sets are described below.

- *Climate.* Leemans and Cramer (1990) have produced climatologies of monthly surface air temperature and precipitation, at 1/2° x 1/2° resolution for the globe, from the available station observations. Lacking a global climatology for soil temperatures, which is one of the parameters required by the conceptual model, we used surface air temperatures instead.

- *Soils.* Information on the global distribution of soil properties was obtained from the database of Zobler (1986), compiled in digital form at 1° resolution from the FAO/Unesco (1974-1982) Soil Map of the World. The two data sets used in this study are major soil units and soil textures. The database of soil units provided the basis for deriving information on two factors important in the production of N₂O - fertility and drainage. Scalars for these factors, ranging from one to five, were associated with each of the 106 soil units as shown in Table 1 and as discussed in some detail below. Since the 1° resolution of the digital databases used here does not reflect the high spatial and temporal variability of field conditions, these indices are employed as relative indicators of soil properties. Moreover, the reliability of the FAO/Unesco soil map is not constant spatially.

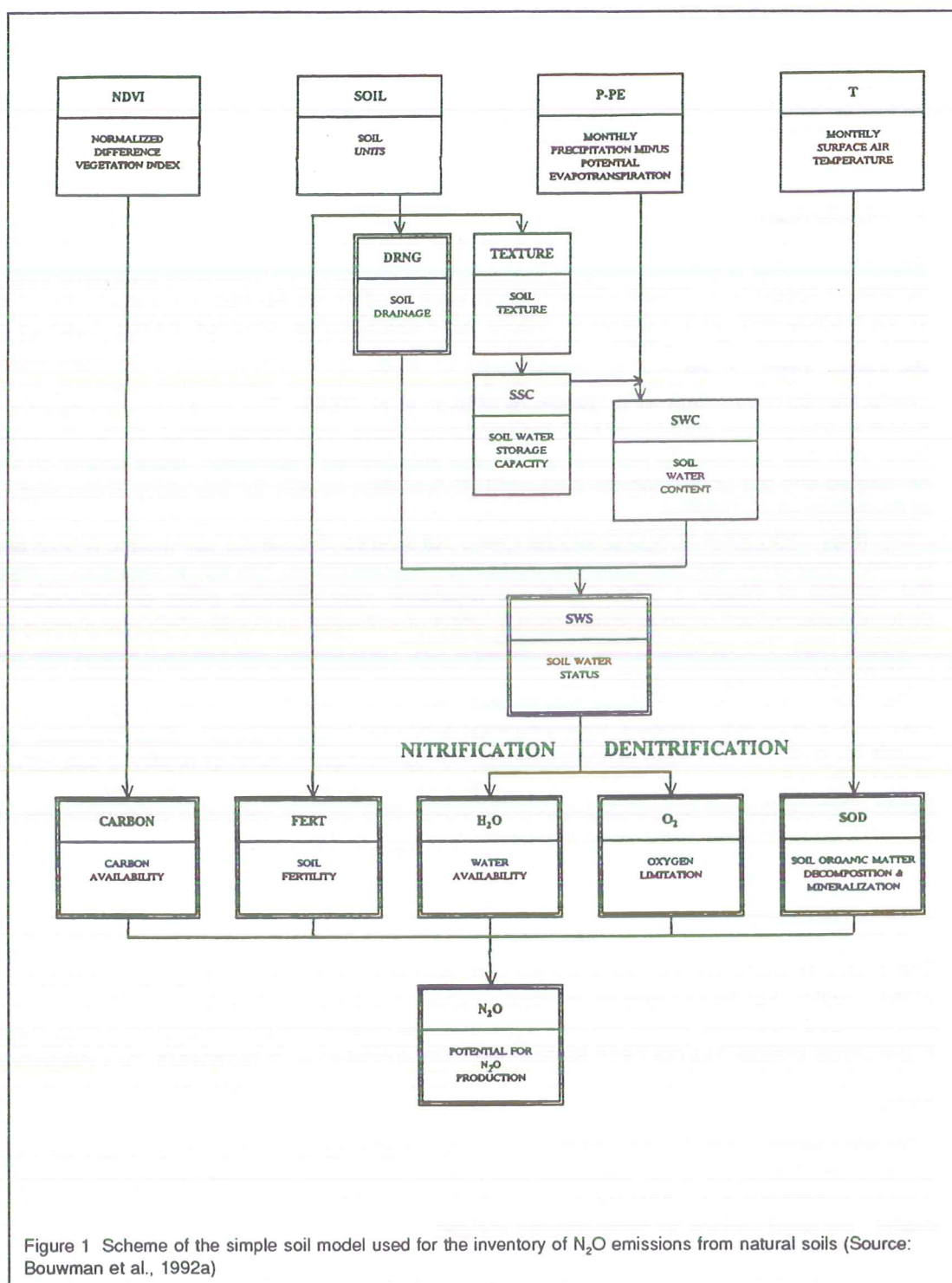


Table 1 Soil clusters (roman numbers), Soil Groups (arabic numbers) and Soil Units within Soil Groups, their areas and scalars for soil fertility (FERT) and drainage (DRNG). Scalars of 1 indicate low fertility and free drainage. Total ice-free land area is 13,239 × 10⁶ ha. Land ice is 1611 × 10⁶ ha (From Bouwman et al., 1992a, based on Zöbler, 1986)

Soil unit	FERT	DRNG	Area (10 ⁶ ha)	Soil unit	FERT	DRNG	Area (10 ⁶ ha)	Soil unit	FERT	DRNG	Area (10 ⁶ ha)
I SOILS WITH PERMAFROST				8 Soils with organic matter accumulation, annual precipitation = evapotranspiration				15 Saline and alkaline soils			
1 Soils with permafrost within 200 cm				9 Soils with organic matter accumulation, annual precipitation < evapotranspiration				VIII SOILS CONDITIONED BY THEIR PARENT MATERIAL			
gelic Cambisols				calcaic Kastanozems				16 Heavy textured cracking soils dominated by clays with swell-shrink properties			
gelic Gleysols				haplic Kastanozems				chromic Vertisols			
gelic Histosols				lucic Kastanozems				pellic Vertisols			
gelic Planosols				V SOILS CONDITIONED BY LIMITED AGE				17 Soils formed in volcanic ash			
gelic Regosols				10 Weakly developed soils				humic Andosols			
II SOILS CONDITIONED BY SUB-HUMID CLIMATES				calcaic Cambisols				mollic Andosols			
2 Soils with illuviation of organic matter and/or sesquioxides				chromic Cambisols				ochric Andosols			
ferric Podzols				dystic Cambisols				vitric Andosols			
gleyic Podzols				eutric Cambisols				18 Weakly developed soils with sand texture			
humic Podzols				ferralic Cambisols				albic Arenosols			
leptic Podzols				gleyic Cambisols				cambric Arenosols			
orthic Podzols				humic Cambisols				ferralic Arenosols			
placic Podzols				lucic Cambisols				lucic Arenosols			
3 Soils with strong textural differentiation with slowly permeable subsoil				VI SOILS CONDITIONED BY WET (SUB-) TROPICAL CLIMATES				IX SOILS CONDITIONED BY THEIR PHYSIOGRAPHIC POSITION			
dystic Planosols				11 Leached soils with argic horizon*				19 Soils influenced by a floodplain regime			
eutric Planosols				ferric Acrisols				calcaric Fluvisols			
humic Planosols				gleyic Acrisols				dystic Fluvisols			
mollic Planosols				humic Acrisols				eutric Fluvisols			
solodic Planosols				orthic Acrisols				thionic Fluvisols			
4 Soils with argic horizon* underlying a bleached subsurface horizon				plinthic Acrisols				20 Soils influenced by groundwater			
dystic Podzolusols				12 Strongly weathered soils with deeply developed argic horizon*				calcaric Gleysols			
eutric Podzolusols				dystic Nitisols				dystic Gleysols			
gleyic Podzolusols				eutric Nitisols				eutric Gleysols			
III SOILS CONDITIONED BY DRY SUBHUMID (SUB-) TROPICAL OR SUBHUMID TEMPERATE CLIMATES				humic Nitisols				humic Gleysols			
5 Soils with argic horizon*				13 Strongly leached soils dominated by hydrated oxides				mollic Gleysols			
albic Luvisols				1114				plinthic Gleysols			
calcaic Luvisols				acric Ferralsols				21 Leptosols (shallow soils, mostly < 10 cm thick)			
chromic Luvisols				humic Ferralsols				2288			
ferric Luvisols				orthic Ferralsols				Lithosols			
gleyic Luvisols				plinthic Ferralsols				Rankers			
orthic Luvisols				rhodic Ferralsols				Rendzinas			
plinthic Luvisols				xanthic Ferralsols				22 Weakly developed soils formed in unconsolidated non-alluvial material			
vertic Luvisols				VII SOILS CONDITIONED BY (SEMI-)ARID CLIMATES				calcaric Regosols			
IV SOILS CONDITIONED BY STEPPE CLIMATES				14 Desert soils				dystic Regosols			
6 Soils with argic horizon* and organic matter accumulation				calcaic Xerosols				eutric Regosols			
gleyic Greyzems				calcaic Yermosols				X ORGANIC SOILS			
orthic Greyzems				gypsic Yermosols				23 Histosols (peat soils)			
7 Soils with organic matter accumulation, annual precipitation > evapotranspiration				haplic Yermosols				dystic Histosols			
calcaric Phaeozems				gypsic Xerosols				eutric Histosols			
gleyic Phaeozems				haplic Xerosols							
haplic Phaeozems				lucic Xerosols							
lucic Phaeozems				lucic Yermosols							
				takyric Yermosols							

* argic horizon = subsurface horizon with distinctly higher clay content than overlying horizon

- *Topsoil texture.* Texture reflects the relative proportions of clay (particles less than 2 μm in size), silt (2-50 μm) and sand (50- 2000 μm). The FAO/Unesco soil maps have only three broad texture classes for the topsoil (0-30 cm): coarse, medium and fine. The reader is referred to the texture triangle in FAO/Unesco (1974) for the distribution of clay, sand and silt in these three classes, and to USDA (1975) for further subdivision of broad classes into minor texture classes. Apart from these three texture classes there are also combinations. The organic class is for nonmineral topsoils.

- *Vegetation.* The satellite-derived normalized difference vegetation index (NDVI) is a measure of primary productivity of the vegetation (Box et al., 1988). The NDVI is the difference between the radiances in the visible (0.58-0.68 μm) and near infrared (0.725-1.1 μm) wavelengths, normalized by the sum of the radiances. The radiances were measured by the Advanced Very High resolution Radiometer (AVHRR) on board the NOAA series of polar-orbiting satellites (Tarpley et al., 1984).

3 Model description

- *Carbon and nitrogen available.* Litterfall and root decay are the major sources of carbon and nitrogen to the soil under natural conditions. Most ecosystems have an abundance of litter on the ground throughout the year. Therefore, the seasonal variation of C and N mobilization in the litter is generally governed by decomposition rates rather than by seasonal variations in litterfall. Here we assumed that the geographic pattern of annual litterfall is the same as that of annual net primary productivity of ecosystems for which the satellite- derived normalized difference vegetation index (NDVI) has been shown to be a good correlate (Goward et al. 1985; Box et al., 1988). Because litterfall is not in phase with productivity, the annual NDVI totals, rather than NDVI for individual months, were used.

Monthly NDVI composites for 1984 were gridded to a $1^\circ \times 1^\circ$ resolution for the globe, and then summed to produce the annual total. Monthly NDVI values range from -0.1 to 0.5, and the annual total range from -0.1 to 4. To be consistent with the other factors used in the study, these NDVI totals were, in turn, rescaled to range from 0 to 10, to obtain the index CARBON. The use of the NDVI captures the variability of NPP at the same resolution of the soil data.

- *Delivery of nitrifiable N.* The rate of carbon and nitrogen delivery is governed by the rate of decomposition and mineralization of soil organic matter, which are regulated by a number of factors including soil temperature, soil moisture, soil fertility and soil texture. All these factors except soil temperature are represented in the other factors (H₂O, FERT). Therefore, we introduced the factor SOD to describe the temperature dependence for the supply of nitrogen and carbon through decomposition of organic matter. The annual input of organic matter is given by the factor CARBON. Lacking a global data set on soil temperatures, we used the monthly climatologies of surface air temperature instead (Leemans and Cramer, 1990) and this would introduce timing errors of up to 1-2 months particularly in middle to high latitudes. SOD is an exponential function describing the temperature effect on N₂O fluxes obtained for semi-arid grasslands (Mosier and Parton, 1985; Parton et al., 1988). $\text{SOD} = 10$ at $T = 50^\circ\text{C}$, and $\text{SOD} = 0$ for $T \leq 0^\circ\text{C}$, with a rapid increase between 10 and 30°C .

- *Soil water and soil oxygen.* A key to distinguishing the pathways of nitrification versus denitrification is the degree of saturation and aerobicity of the soil. These are in turn, determined by the amount of water present in the soil (i.e. the soil water content, SWC) versus the maximum amount of water allowed in the soil (i.e. the soil water storage capacity, SSC), as well as by the soil drainage properties. Topsoils are the most important sites for N₂O production. Maximum microbial activity and the most intensive rooting occur in the top soil layer (Seiler and Conrad, 1981; Denmead et al., 1979; Goodroad and Keeney, 1985). Therefore, we consider the topsoil, i.e. upper 30 cm of the soil profile, as the zone where N₂O production takes place. Some physical properties of the zones below 30 cm, that influence water and air movement in the topsoil, are given by the soil drainage characteristics. Below the soil water storage capacity, the soil water budget model to estimate monthly topsoil water content, the effect of drainage to derive the soil water status (SWS), and the resulting indices H₂O and O₂ will be briefly discussed.

- *Soil water storage capacity.* A first step in modeling the water balance of the topsoil is the determination of the soil water storage capacity. SSC is the total amount of water held in the upper 30 cm

of the soil profile at field capacity (soil water potential of 10 kPa = 0.1 bar), i.e. when after wetting the internal drainage and redistribution have ceased. The soil water storage capacity (SSC) is derived from the soil texture class for most soils (Table 2), based on Euroconsult (1989) and Landon (1984). The effect of stoniness is not considered. For several soils with special physical properties influencing field capacity, alternative water storage capacities were assigned regardless of soil texture.

- *Soil water budget model.* The monthly change in soil moisture is the difference between the supply and demand of moisture at the surface. Supply is governed to a large extent by precipitation, while demand is governed by evaporation through soils and transpiration through plants. Runoff (on sloping land) or ponding (on level land) occur when the net input of water exceeds soil water storage capacity (SSC) minus the initial amount of soil water, after drainage has been accounted for.

A soil moisture model was used that is simple in design, and whose solution does not depend on an arbitrarily chosen initial condition. We adapted the Mintz and Serafini (1981) model for the calculation of the monthly soil water content. In this model, net supply is the difference between monthly precipitation (P_m) and evaporation from wet canopies (EI_m), while demand is sum of transpiration through plants and evaporation from soils (ETS_m):

$$SWC_m = SWC_{m-1} + (P_m - EI_m) - ETS_m$$

Potential evaporation (PE_m), a measure of the maximum demand for moisture by the atmosphere, was calculated from the surface air temperature according to Thornthwaite (1948). Mean monthly surface air temperatures (T_m) and precipitation (P_m) were obtained from Leemans and Cramer (1990). For simplification, precipitation in the form of snow is treated as rainfall. Three moisture regimes were considered, dependent on the relation between P_m and PE_m :

- $P_m = 0$	$EI_m = 0$ $ETS_m = PE_m \times \beta_m \times \alpha$
- $P_m < PE_m$	$EI_m = P_m$ $ETS_m = (PE_m - P_m) \times \beta_m \times \alpha$
- $P_m > PE_m$	$EI_m = PE_m$ $ETS_m = 0$

where:

$$\alpha = 0.4; \text{ and}$$

$$\beta_m = 1 - e^{-\gamma [(SWC_{m-1} + (P_m - EI_m)/2) / (SSC - \delta)]}$$

The coefficient α expresses the ratio of the amount of water extracted from the topsoil (0-30 cm) to the extraction from the full rooting zone (as noted before, we consider only the topsoils). The function β describes the maximum water extraction as a function of soil water content and soil characteristics. Its parameter γ depends on topsoil texture and mineralogy, while δ represents the water unavailable to plants, i.e. the intercept of the water extraction curve β . The values of δ and γ are in given Table 2. For clays, $\gamma = 6$, resulting in a strong decrease in water extraction below $SWC/SSC \sim 50\%$. Due to the selected value of δ for clays, water extraction at $SWC/SSC < 10\%$ is reduced. In sands and medium textured soils β sharply decreases at values of SWC/SSC of about 40% and 20 %, respectively. Because SWC is a function of β the monthly equilibrium SWC is achieved independently of the initial water content at the start of the simulation. For more details we refer to Bouwman et al. (1992a).

- *Effects of soil drainage.* Drainage is a property of the soil which determines how excess water is removed from the soil, and is also an indicator of soil aeration. The soil drainage indices (DRNG) were associated with soil units based on several soil properties including the presence impermeable and less permeable horizons as presented in Table 1. It is difficult to describe in the model quantitatively the effects of drainage on soil oxygen limitation and water content. Adding diffusion at the base of the "bucket" may be an appropriate approach, but the values of diffusion coefficients for different drainage are not well known. Here, the factor soil water status (SWS) was introduced, an index of the water saturation when drainage effects are considered.

- *Soil water status.* The soil water status SWS of the topsoil is scaled on the basis of soil water content (SWC) and drainage (DRNG) as shown in Table 3. Although it is difficult to combine drainage and

SWC/SSC at their intermediate values in the SWS index, we noted several points: (i) distinguishing saturation levels <20% is not important; (ii) we linearly increased the SWS scale up to the saturation scale; (iii) for intermediate values of SCW/SSC N_2O production would likely asymptote at high saturation and poor drainage. It is clear that the highest SWS rank of 10 would be assigned to a poorly drained soil when the monthly soil water content SWC is close to the storage capacity SSC of the soil. There is much arbitrariness in the SWS scale. It nevertheless represents a first attempt at quantifying our descriptive understanding of the effects of soil drainage characteristics on soil oxygen and soil moisture.

Table 2 Soil Water Storage Capacity (SSC) for the upper 30 cm. SSC is shown for the major texture classes and for some soil types (FAO/Unesco, 1974) with limited soil depth or with clay minerals having specific soil moisture retention characteristics. Based on Landon (1984) and Euroconsult (1989). Source: Bouwman et al., 1992a)

Soil texture	SSC (mm)	γ^a	δ^a
coarse	40	15	0
coarse/medium	60	9	0
organic	60	18	0
coarse/fine	80	9	0
coarse/medium/fine	80	9	0
medium	80	9	0
medium/fine	100	9	0.1
fine	120	6	0.1
Soil type*			
<i>Rendzinas</i>	15	15	0
<i>Lithosols</i>	15	15	0
<i>Rankers</i>	15	15	0
<i>Vertisols</i>	60	6	0.1
<i>vertic Cambisols</i>	80	9	0.1
<i>Ferralsols</i>	80	9	0
<i>vertic Luvisols</i>	80	9	0.1
<i>Andosols</i>	120	9	0

* a full list of soil units, their fertility, drainage and PH scales is presented in Table 1; γ and δ are used in the computation of transpiration and soil evaporation from the soil water content; δ expresses the intercept of the soil water extraction curve β

Table 3 Scaled Soil Water Status (SWS) based on soil drainage and modeled soil water content / soil water storage capacity (SWC/SSC). Source: Bouwman et al., 1992a)

SWC/SSC (in %)	Drainage Scale				
	1	2	3	4	5
1 0 - 20	1	1	1	1	2
2 20 - 30	2	2	2	2	3
3 30 - 40	3	3	3	4	5
4 40 - 50	4	4	4	5	7
5 50 - 60	5	5	5	6	8
6 60 - 70	6	6	6	7	9
7 70 - 80	6	7	7	8	9
8 80 - 90	7	7	8	9	10
9 90 - 100	7	8	9	10	10
10 Surplus (>100%)	8	9	10	10	10

Table 4 Scaled oxygen limitation (O₂) for experiments 1-5 and 7. O₂ is based on the soil water status (SWS, see Table 3) in current month and preceding month. In experiment 6 the factor O₂ = SWS for the current month. Source: Bouwman et al., 1992a)

SWS in preceding month	SWS in current month									
	1	2	3	4	5	6	7	8	9	10
1	1	1	1	4	6	8	10	10	10	10
2	1	1	1	4	6	8	10	10	10	10
3	1	1	1	3	5	7	9	10	10	10
4	1	1	1	3	4	6	8	9	10	10
5	1	1	1	2	3	5	7	8	9	10
6	1	1	1	1	2	4	6	7	8	9
7	1	1	1	1	2	3	5	6	7	8
8	1	1	1	1	2	3	4	5	6	7
9	1	1	1	1	2	3	4	5	6	7
10	1	1	1	1	2	3	4	5	6	7

Table 5 Scaled of soil water availability (H₂O) for experiments 1-5 and 7. H₂O is based on soil water status (SWS, see Table 3) in current month and preceding month. The H₂O scale corresponding to the SWS in the current month only, as used in experiment 6, are presented in the last two columns. Source: Bouwman et al., 1992a)

SWS in preceding month	SWS in current month										H ₂ O EXP 7	
	1	2	3	4	5	6	7	8	9	10	SWS current month	H ₂ O
1	1	2	4	6	9	10	10	10	6	1	1	1
2	1	1	3	5	8	9	10	10	6	1	2	1
3	1	1	2	4	7	8	9	10	5	1	3	2
4	1	1	2	4	7	8	8	8	4	1	4	4
5	1	1	2	4	6	7	7	7	3	1	5	6
6	1	1	2	4	6	7	7	6	2	1	6	7
7	1	1	2	4	6	7	7	6	2	1	7	7
8	1	1	2	4	5	6	6	5	2	1	8	5
9	1	1	2	3	4	6	6	4	2	1	9	2
10	1	1	2	3	4	5	6	4	2	1	10	1

Effects of soil water and oxygen status on nitrification and denitrification. We derived two factors, water availability (H₂O) and oxygen limitation (O₂) as indices for nitrification and denitrification potentials, respectively. The factor H₂O (see Table 5) describes the effects of soil water on mineralization and nitrification processes and can be regarded as the complement of O₂. In general, water contents of 60-80% of field capacity are considered favourable for soil organic matter decomposition, mineralization and nitrification. Nearly saturated and anaerobic soils have low scalars. H₂O is based on the SWS in the previous and current months. Wetting of dry soils is considered more favorable than soils with constant water content. Although we did not attempt to simulate the reported pulses in N₂O production after the wetting of dry topsoils, we hypothesized that pulses of N₂O at the onset of a wet season would give a higher average monthly N₂O flux than that in wet months preceded by moist conditions. (This hypothesis was tested in one of the sensitivity experiments in which H₂O is based on the soil water status in the current month only).

The factor O₂ (Table 4) expresses effects of oxygen limitation on denitrification. It is obtained from the soil water status (SWS) for the current month and SWS during the previous month to include the effect of wetting and drying of soils (see under H₂O). The oxygen limitation at soil water contents of 60-80% are considered most favorable for N₂O production by nitrifiers, while at water contents of >80%, denitrifier N₂O production is most prominent. In general high degrees of wetness result in high O₂, and

wetting is assigned higher scalars of O₂ than constantly wet or moist soils.

- *Soil fertility.* The last control on N₂O production we need to quantify is soil fertility. Soil fertility refers to the inherent capacity of a soil to supply nutrients (see e.g. Sanchez, 1976; Brady, 1976). The concept of soil fertility used in this study does not include the supply of nutrients by mineralization of organic matter. The latter is given by the factors CARBON and SOD. Important soil characteristics for inherent fertility are soil pH, cation exchange capacity, base saturation, alumina saturation, amounts of weatherable minerals and phosphorous fixation. Soil fertility was scaled on the basis of the 26 general FAO/Unesco soil groups; the indices for some individual soil units within groups vary due to their diagnostic horizons or properties (see Table 1).

4 N₂O potential

There are many ways to combine the factors. Lacking information about relative importance, we assumed that all five controlling factors are of equal importance, i.e. the maximum fertility factor has the same effect as the maximum oxygen limitation factor as far as N₂O production is concerned. Hence, although FERT was scaled from 1 to 5 because of our inability to discriminate further, FERT was multiplied by two to normalize to the other factors.

The non-dimensional N₂O production was modelled every month as the geometric mean of all five controlling factors. In this way, a low value for one of the factors automatically lowers the N₂O production index. For example, values of 1 and 9 for two factors are given less weight than 5 and 5, which yields the same arithmetic mean.

The monthly non-dimensional N₂O production is calculated as follows:

$$N_2O = [O_2 \times H_2O \times SOD \times FERT^* \times CARBON]^{1/5}$$

where N₂O, O₂, H₂O and SOD are indices calculated monthly; FERT* = 2xFERT, FERT being the fixed soil fertility index; and CARBON is also a fixed value equal for all months.

Under conditions where soil processes are inactive, i.e. in months with mean surface temperatures <0 °C, the factor SOD = 0, and therefore, N₂O = 0. The N₂O scalar was set to 0 for months for which both the mean monthly precipitation and the soil water content equal zero (P = 0, SWC = 0). When there is rainfall (P > 0) and the water budget equation predicts a dry soil at the end of that month (SWC = 0), the soil has not been dry throughout the month. In that case the indices for O₂ and H₂O are low, resulting in low N₂O values.

5 Results

Detailed analysis of the model results can be found in Bouwman et al., 1992a), who made a comparison and sensitivity analysis of the model. The results for the above equation for the N₂O index is shown in Figure 2. The correlation coefficient of the regression line is about 0.6. The emissions for the land cover types used in this study can be found in Bouwman et al. (1992b). A short analysis of the global model results is given below.

The most important soil groups, in terms of areal extent and N₂O potential, are the Ferralsols (Table 1, group 13). Due to their occurrence in somewhat drier climates, the Acrisols (group 11) show slightly lower N₂O scalars than Ferralsols, while the fertile Nitisols (group 12) have higher scalars than Ferralsols. The extensive subtropical and tropical Luvisols (group 5A) also have high scalars. Other soils with high scalars, but occupying minor areas, are tropical Podzols (group 2A), Vertisols (group 16), Andosols (group 17), Fluvisols (group 19) and Gleysols (group 20). The subtropical Phaeozems and Kastanozems (groups 7A and 9A, respectively), occurring mainly in South America, exhibit high N₂O scalars, but their global effect is moderated by their small areas. Their temperate counterparts (7B, 9B) show much lower N₂O scalars. Another soil group of significant area (2300 x 10⁶ha) is the group of shallow soils (group 21). The model predicts that the temperate shallow soils, when covered by their natural forest vegetation, have very low potential N₂O production, while tropical Leptosols are intermediate.

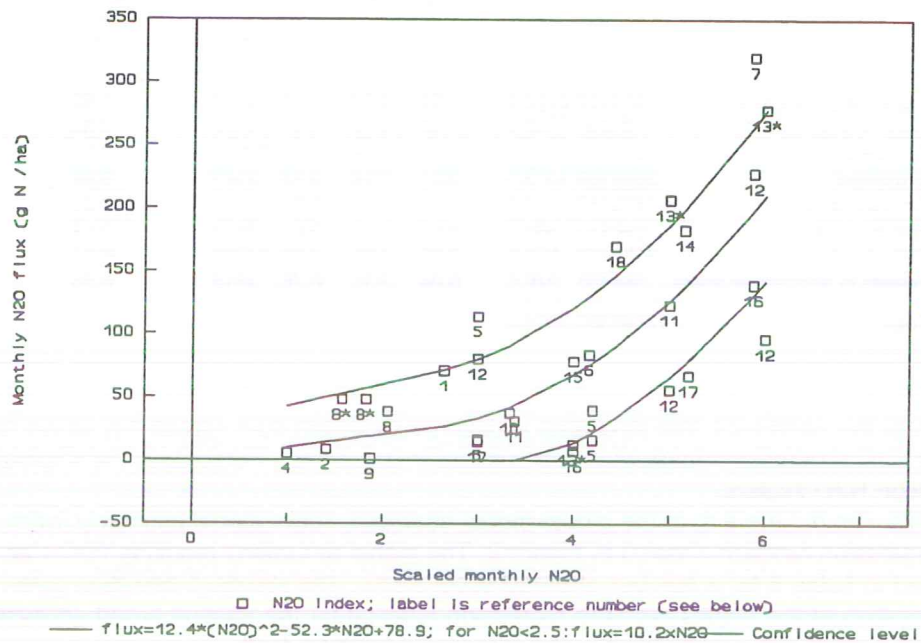


Figure 2. Relation between modelled N2O index and measured monthly flux measured in a number of different sites, regression line and upper and lower confidence levels.

The markers indicate the following references:

1 = Mosier et al. (1981); 2 = Parton et al. (1988); 3 = Seiler and Conrad (1981); 4 = Cates and Keeney (1987); 5 = Goodroad and Keeney (1984a); 6 = Duxbury et al. (1982); 7 = Keller et al. (1983); 8 = Schmidt et al. (1988); 9 = Bowden et al. (1990); 10 = Smith et al. (1983); 11 = Hao et al. (1988); 12 = Keller et al. (1986); 13 = Matson and Vitousek (1987); 14 = Luizao et al. (1989); 15 = Livingston et al. (1988); 16 = Matson et al. (1990); 17 = Vitousek et al. (1990); 18 = Keller et al. (1988); * = points where parameters were selected based on reported conditions; soil, climate and NDVI data were different from the actual conditions

Table 6 Estimate of global natural N₂O emission based on regression analysis of modelled N₂O index and measured fluxes at a number of locations. The standard deviations reflect the deviation within the broad ecosystems listed using the regression function. They do not reflect the uncertainty interval presented in Figure 2

Type	Area (10 ³ ha)	Emission 10 ⁹ g N ₂ O-N y ⁻¹	Min (kg N ha ⁻¹ y ⁻¹)	Max (kg N ha ⁻¹ y ⁻¹)	Mean (kg N ha ⁻¹ y ⁻¹)	Number of grid points	Standard deviation (kg N ha ⁻¹ y ⁻¹)
Closed tropical forest	1625360	2292.2	0.05	3.36	1.41	5406	0.60
Open tropical forest	781001	838.1	0.08	3.23	1.07	2592	0.55
Temperate forest	2021766	494.1	0.01	2.58	0.24	12012	0.24
Grassland	2342182	1013.3	0.01	3.08	0.43	9167	0.44
Agricultural land	1472167	1043.3	0.01	3.11	0.71	7262	0.52
Human area	586216	383.7	0.01	3.11	0.65	2874	0.52
Other land	3551458	664.0	0.00	2.69	0.19	17700	0.21
Forests in agricultural areas	365403	276.0	0.04	3.11	0.76	3813	0.56
Total	12745550	7004.6					

About 15% of the earth's ice free land area is covered by desert soils (group 14) which have low potential for N₂O production mainly due to precipitation limitations. Particularly the tropical peat soils show high N₂O scalars.

Although this was not the aim of the global model described, some global estimates were made using the regression function showed in Figure 2. The global emissions resulting from that analysis are presented in Table 6 for a number of broad ecosystems. The standard deviation given is the standard deviation of the results from the regression function for the various broad ecosystems. This does not include the uncertainties in the regression function itself.

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Controlling factors of methane emission from rice fields

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During the 1991 wet season (Sept.-Dec.) and the 1992 dry season (January-May) methane emissions from rice paddies at the IRRI research farm were monitored with a closed chamber technique as described by Schütz et al. (1989) with small modifications. The field experiments concentrated on the impact of different soil types and mode of nitrogen fertilizer application. The data from these field- and additional laboratory experiments illustrate the impact of different soil types and N fertilization on overall methane emissions from wetland rice fields. Emissions during the dry season are significantly higher than in the wet season. The data show that soils can be ranked according to their capacity to produce methane.

In a recent paper Bachelet and Neue (1992) reviewed and replicated 3 published techniques to estimate global methane emissions from rice paddies. We will compare the different approaches and our field data in order to produce a better concept for extrapolation of emission data from field experiments. The major components of this concept to decrease the uncertainties of global methane emissions will be

- soil type
- carbon input
- climate, temperature, water regime
- cultural practices
- total rice crop biomass

Based on this concept we will single out major gaps in knowledge that prevent us from making better global estimates of the source strength of wetland rice fields.

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METHANE EMISSIONS FROM CHINESE RICE FIELDS AS INFLUENCED BY DIFFERENT FERTILIZERS

The results presented were obtained at two stations for semi-continuous measurements of methane emissions located in two of the major rice growing areas of China (Zhejiang and Hunan Province). The measurements at Hangzhou (Zhejiang Province) encompassed the amendments of potassium, rape seed cake and barnyard manure. The data set obtained over 5 vegetation periods reveals pronounced interannual variations that showed similar patterns independent from fertilizer treatments. The mean emission rates observed in 1988 ($10.9 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$) were significantly lower than in 1987 ($38.8 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$) and 1989 ($44.6 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$). The amplitude of interannual variations clearly exceeds the fertilizer induced effects as realized in this field experiment, i.e. an excessive addition of potassium fertilizers (694 kg KCl/ha in early seasons and 694 kg K_2SO_4 /ha in late seasons) and organic amendments in the range of 1000 kg/ha. Integrated over the entire observation period, the mean emission rates were 30.4 (no fertilizer), 27.5 (potassium fertilizer), 28.3 (potassium and organic fertilizer), and 35.1 $\text{mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ (organic fertilizer).

A different approach was employed for the field design at Tao Yuan (Hunan Province). The amount of incorporated fertilizers were calculated according to the NPK ratio. The preliminary results of this experiments that is currently continued consists of 2 intervals of 4 weeks in the early and late vegetation period in 1991. Although this data base does not suffice for an overall estimate of the methane flux, the results clearly reveal pronounced differences in the field plots investigated. The consequent use of mineral fertilizers (without any incorporation of organic matter) significantly reduced methane emission; the effect of organic manure depended on the type of organic material used.