Foreword

In the public debate about the benefits and risks of agrochemicals, food safety and environmental protection have rightly received special attention against the background that several hundred pesticides are nowadays being used worldwide and that the general public is afraid of, or at least averse to, pesticides. Researchers in academia, government, and industry should consider it a continuing challenge to explain clearly the nature of the problems and of the experimental approaches. While regulatory efforts are directed to reducing pesticide use in agriculture, research is aiming at further improving the use and safety of pesticides, particularly by the promotion or development of compounds which can be used in small quantities with high specificity, are readily degradable and environmentally "friendly".

In order to assess environmental safety, research is needed to acquire information on the long-term fate and effects of pesticides in the agro-ecosystem. This research is, to a considerable extent, dependent on valid and reliable experimental models. The better the model simulates "nature", the better will be the possibility of extrapolating results to real-world situations. Results from experimental studies, incidentally, are also needed to provide factual support to mathematical models used to "predict" the environmental behaviour of pesticides.

Lysimeters have been applied to the needs of pesticide research for some 20 years now. In the early 70's, laboratories developed lysimeters, filled with "monolithic" soil blocks or cores, and began using radio-labelled compounds in outdoor lysimeter-type devices. This led, especially in Germany, to the development of a standardized agro-ecosystem approach in which labelled pesticides are applied to undisturbed soil, simulating Good Agricultural Practice.

In two Workshops, organized in the Federal Republic of Germany in 1989 and 1990 (at the Nuclear Research Centre, Jülich, and at the L.L.F.A. in Neustadt), the basic prerequisites for the conduct of such lysimeter experiments were discussed, and experience gained thus far was exchanged. Pesticide regulatory agencies in Germany have now included this experimental approach in the procedures used for assessing the long-term, especially the leaching, behaviour of pesticides in an agricultural ecosystem. Experience with this technique is beginning to accumulate.

This monograph, edited by experts of high renown in the field, presents descriptions as well as pro's and con's of lysimeter arrangements now in use for studies with labelled pesticides. It is the first treatise dealing solely with this important technique. It will contribute to improving the understanding of, and expedite approaches to the experimental elucidation of the fate of pesticides in the environment and their performance in the plant/soil and soil/water systems. And it will certainly promote continuing discussions which – hopefully – can provide answers to a number of questions some of which extend beyond the narrow scientific issues. One is whether regulatory action can be based solely on results obtained from lysimeter experiments. A second is the

extent to which leachates from lysimeters can be used to assess the likely pesticide concentrations in the groundwater. After all, if maximum use is to be made of lysimeters, they must be well understood, otherwise they are just measuring instruments.

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1.
Introduction

1. INTRODUCTION

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The seemingly perpetual chase by agriculture to keep pace with the world population increase is so well known as to be taken for granted and sometimes it even appears to be forgotten. A few basic statistics are therefore worthy of repetition.

The population of the world in 1989 was 5.2 thousand million and the annual rate of increase was about 100 million. Projected forward this gives a population of 11 thousand million in 2050 (Finney, 1990). Against this, while only about 50 % of the world's land that has agricultural potential is in use this figure rises to around 90 % in the highly populated areas of Europe and Asia. Most of the remaining area will be expensive to develop either in financial terms, for example if aridity and/or salinity must be overcome, or in ecological terms, for example, if tropical rain forests are converted into arable land. Also, the existing stock of agricultural land is being reduced by urbanization at a rate of about 0.6 % per year. In addition about 0.4 % of the fertile land is lost per year due to erosion, irrigation enforced salinization and overgrazing leading to desert formation. For these reasons the area of arable land is expected to increase by only about 2.9 % by the year 2000 (FAO 1981) which means the arable area per head of population will decline from 0.3 ha (1981) to 0.22 ha (2000) and, using Finney's population projection, to about 0.13 ha in 2050. This implies yields must increase by 230 % between 1981 and 2050 just to maintain current levels of nutrition which are self-evidently inadequate in many parts of the world. Such a yield increase is equivalent to an annual (compound) rate of increase of almost 2 %. This seems, perhaps, to be a modest target given that the annual rate of increase for all food (including fish) for the period 1961-88 was 3.67 %. This, however, is the sort of calculation that may be appropriate to the financial markets but is of dubious applicability to agriculture where production must, at some stage, run up against a limiting factor such as availability of water, nutrients or even photosynthetic efficiency. There can be no doubt that such a sustained increase can only be approached by intensifying production and using the most advanced technology.

Such technology includes the use of pesticides. Regrettably, the subject of agrochemicals has been brought into the political arena, particularly in the developed countries, so that decisions concerning their use are increasingly constrained by political considerations. Whilst this may be seen as a triumph of western-style democracy, it does not help

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seen as a triumph of western-style democracy, it does not help efforts to increase agricultural productivity. In fact in a related issue, that of the level of food reserves to be maintained, government policies in Europe and North America have successfully reduced world food stores to levels that have been regarded by FAO to be positively dangerous (Finney, 1990). It may be safe to assume that policies to reduce food production in developed countries will not continue forever but certainly their application in recent years has provided a useful background for those opposed to the use of modern agricultural techniques.

Critics of pesticide technology are particularly concerned about possible effects on the quality of food and about effects on the environment. These are also the concerns of the manufacturers and users of pesticides and of agriculturalists. The reasons underlying the concerns are common to both groups of protagonists despite appearances to the contrary. Indeed those engaged in activities which use pesticides recognise that they are under an unequivocal obligation not to use pesticides in ways that harm the environment (and certainly not to produce food that poisons the consumer!).

What seems to be lacking is a common philosophical base from which to address the issues. For example, the extreme view, that "harm" is caused by the mere presence of a man-made chemical even if there is no demonstrable biological effect, is particularly difficult to counter with scientific argument simply for this reason.

A balanced approach should surely take into account the other effects of man's activities to provide a proper perspective. The practice of any form of agriculture, or even systems of hunting and gathering, inevitably brings about ecological consequences since the aim of settled agriculture is to replace the indigenous climax vegetation with plants that are more useful to man. Thus agriculture is ecologically (or thermodynamically) unstable and therefore can only be maintained by the input of energy. Traditionally this has been provided largely in mechanical ways but modern technology allows the use of energy in a chemical form to supplement or replace older techniques. Agricultural crops provide a different habitat to mixed climax vegetation so the species composition of wild flora and fauna changes whether or not the agricultural system uses chemicals. The changes vary geographically, with cropping pattern and with the technology that is used. Thus it is important to evaluate pesticides not against some arbitrary (often imaginary) baseline but against the consequences of using alternatives to attain the objective.

Evaluations of this sort do not, of course, always give clear answers. A good example is provided by a comparison of mechanical soil tillage with no tillage using herbicides for weed control. Mechanical treatments can reduce the populations of soil inhabitants by up to 90 % (Somerville, 1987) and increase the risk of soil erosion. No tillage systems reduce erosion, use less energy and increase water infiltration

(Radcliffe et al., 1988) but the latter may increase the possibility of pesticides reaching groundwater (Isensee et al., 1990). In addition, weed and disease problems may be more intractable with minimum tillage and, on at least some soils, yields tend to be lower, see for example Touchton and Johnson, (1982). Thus no general conclusion can be drawn about the "ideal" system of cultivation.

Consideration of toxicological issues also frequently ignores relativities. As Graham-Bryce (1989) pointed out, most herbicides introduced in the last 20 years have acute LD_{50} values for rat that are lower than that of aspirin and certainly lower than that of caffeine. He also drew attention to the work of Ames et al. (1987) which showed that the relative carcinogenic hazards from the average dietary intake of DDT/DDE and ethylene dibromide were several orders of magnitude lower than those of naturally occurring carcinogens such as aflatoxin in peanuts or hydrazines in mushrooms (not to mention ethanol in alcoholic beverages!)

Provided this criterion is borne in mind it is undoubtedly the duty of responsible government to ensure that pesticides are used in such a way that they provide minimum additional toxicological and environmental hazard. To this end a variety of test procedures has been developed with which to evaluate the toxicological and environmental acceptability of new and existing plant protection materials. Such tests now include, in addition to the well established toxicity studies with mammals as models for man, studies with a range of bird, fish and insect species, soil flora and fauna and of the environmental fate of the active molecule and its major transformation products. It is equally the duty of scientists to ensure that the procedures and their interpretation are as valid and reliable as possible. Not only must consumers and the environment receive adequate protection but also materials that can help in the struggle to raise agricultural productivity must not be rejected unnecessarily. In the latter context it is particularly important that chemicals are not denied to developing countries for reasons that are irrelevent to them. Proposals to prevent the export of agrochemicals from countries where they are manufactured but not registered, even if they have no identified use in the country of origin but will be valuable elsewhere, are misguided if not positively misanthropic.

The objects of this monograph include an evaluation, in the light of this obligation, of procedures to study the fate of pesticides in the soil and sub-soil, with particular reference to lysimeters using radio-labelled compounds.

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2.
Methods to study Fate and Behaviour of Pesticides in the Soil

2. METHODS TO STUDY FATE AND BEHAVIOUR OF PESTICIDES IN THE SOIL

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ABSTRACT

Registration procedures usually require standard laboratory measurements supplemented by other laboratory studies and field observations. The limitations and advantages of various methods used to assess degradatio pathways, persistence and mobility are discussed. It is suggested that lysimeter systems have a number of advantages compared with other methods because they almost exactly reproduce the field environment and agricultural practice, they are easier to monitor than field experiments and radioisotopes can be used. The results obtained integrate the processes that are normally measured separately in the laboratory. Their main disadvantages are expense, environmental factors can be measured but not controlled and they may not reflect field variability.

Type of information that is required

Many governments have issued guidelines, in some cases requirements, for the data they need to evaluate the environmental acceptability of a pesticide. For the purposes of this discussion, the FAO (1989) draft guidelines provide a convenient basis as they avoid specific national pre-occupations and they have also been incorporated in the GIFAP (1990) criteria.

At the beginning, the FAO draft makes the important point that "Research resources should be focussed on the identification and evaluation of major risks and data requirements which are excessive and stifle innovation must be avoided." It is to be hoped that this sentiment gains the widest possible acceptance for the reasons discussed in chapter I. In the document the principle is applied by recommending a 4-step, sequence of tests of increasing complexity (and cost). By assessing the risks and benefits following each step the need for further testing can be determined. The statement, "Tests closer to practical use conditions may be required if there are doubts that benefits clearly outweigh risks" implies that a compound could be classified as acceptable at step 2 or even step 1. In practice this doesn't happen; whilst a compound might be rejected at an early stage of the evaluation (this would normally be an action taken by the manufacturer) it is

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almost unthinkable that, currently, a compound could obtain registration without evaluation at all levels of the sequence.

The steps are:

1. Standard Data/Laboratory tests
   Physico-chemical properties of the AI and the formulated product; mobility of the active ingredient (adsorption/desorption/leaching in soil); methods of analysis.

2. Supplementary Laboratory tests
   These depend on the properties and intended uses of the product. They may include degradation in water and sediments, leaching of major degradation products, photolysis on soil surfaces and estimation of volatility (e.g. from soil).

3. Simulated Field and Field Trials
   It is envisaged that these will be necessary for compounds that appear to be relatively persistent or mobile on the basis of the results from steps 1 and 2.

4. Post-registration Monitoring
   This involves monitoring residues in soil, water and wildlife, preferably combined with biological assessments, during normal commercial use.

The Guidelines then go on to list procedures considered to be appropriate for the various steps. Those concerned with fate and mobility in the environment include standard laboratory techniques for incubating soil with pesticides, adsorption/desorption measurements, soil TLC, soil (leaching) columns, lysimeters and field leaching. This conventional approach is based on the (in this case unstated) premise that there are correlations between field behaviour and appropriate laboratory tests so that often it will be possible to avoid the expense of field investigations given adequate laboratory data. Thus, only in borderline cases should extensive field work be neccessary. An additional consideration is that it is possible to limit the number of variables in laboratory studies so that results tend to be more reproducible than those obtained in the field. Whilst this may make life slightly easier for registration authorities, it is arguable that the avoidance of a proper consideration of field variability will reduce the quality of any decisions that are taken.

At this point it might be useful to compare some aspects of laboratory and field experiments with regard both to experimental conditions and results.

<u>Experiments to assess degradation pathways and persistence</u>

The FAO guidelines make the points that knowledge of whether a pesticide is degraded by microbial, chemical or photochemical mechanisms is of limited relevence from the point of view of environmental safety and that where both chemical

and microbial processes occur the products are often identical. Such generalisations are really valid only in particular contexts. The first is acceptable in relation to field measurements of persistence but clearly, when deciding what laboratory studies of degradation would be appropriate, it is necessary to know which processes will operate. The similarity between chemical and microbiological (i.e. biochemical) pathways of degradation is certainly not always true. For example the chemical decomposition of the chloro-triazines is a hydrolysis to produce the corresponding hydroxy-compounds, whereas biological transformation usually proceeds either by N-dealkylation or by conjugation with glutathione. A different situation occurs when considering compounds which produce "bound" residues, which with a few notable exceptions, are produced only biologically (using the term to include extracellular enzymes). Perhaps the FAO attitude would be that these differences between chemical and microbiological reactions are of little or no consequence for the environment; this is plausible but could be vulnerable to new evidence and is unsatisfying philosophically if the view is taken that the ultimate fate of all anthropogenic chemicals should be known.

The relative importance of the various pathways of dissipation depends on the chemical and the conditions to which it is exposed. Usually it is assumed, unless there is strong contrary evidence, that in the soil pesticides are degraded largely microbiologically. The rate of such processes depends on the availability of the pesticide, the number of organisms capable of degrading it and their level of activity. The second and third of these factors are controlled by soil temperature, moisture, aeration, nutrient status and pH (Frehse and Anderson, 1983). These considerations apply to a soil in a stable condition. However, soil is essentially like a fragile tissue so its biological activity is easily disturbed by insensitive handling. In particular, commonly used laboratory procedures such as prolonged storage, air drying, freezing, thawing and seiving can reduce microbial biomass several fold (see Walker, 1989, for examples). Further, microbial activity declines during the course of a laboratory incubation whether measured by a process, such as CO_2 evolution (Guth, 1980), or as biomass (Anderson, 1987); 50 % reductions in 70-90 days are not unusual.

Another deficiency in laboratory incubation studies is that they frequently do not include growing plants, yet rhizosphere organisms are known to be largely responsible for the microbial characteristics of soil in the field (Greaves and Malkomes, 1980). Admittedly, as far as pesticide dissipation is concerned, studies which compare planted with unplanted soil have not always found differences, at least in experiments in pots (Seibert et. al, 1981; Mudd et. al. 1983; Cheng et. al., 1975, for example) although effects with decaying plant material frequently have been seen (Cheng et. al., 1975; Seibert et. al., 1981, 1982). In the field, results are complicated by the greater water loss from cropped than uncropped plots so there are reports of increased dissipation in the presence of plants (Sikka and Davis, 1966), reduced

dissipation (Birk and Roadhouse, 1964) and no differences (Hance et. al., 1978). A related factor is that, at least for some compounds, microbial communities can degrade compounds more effectively in laboratory systems than single species populations (Slater and Lovatt, 1984). Although there seems to be no experimental evidence, it is reasonable to expect that the environment of a laboratory incubation will sustain a different microbial community to that which occurs in the same soil in the field.

Comparisons of laboratory and field persistence have been made using laboratory data obtained at a range of (constant) temperature and moisture conditions together with a simulation model that takes account of daily fluctations in temperature and soil moisture in the field (reviewed by Walker, 1989). Almost always the predictions from laboratory data overestimate residues measured in the field. This must be partly because the model ignores possible losses by volatilization and photodecomposition. Note here that, although the FAO guidelines recommend studies to estimate these processes in isolation they do not include specific suggestions as to how such measurements can be integrated with other measured processes of dissipation. Another limitation of the model is that laboratory observations are made at a series of constant environmental conditions whereas in the field, soil experiences daily temperature and moisture fluctuations.

Kubiak (1986) found that the rate of metamitron mineralisation at a constant 22°C was about half that which occured in a regime fluctuating between 10°C and 25°C but with daily average temperatures of always below 22°C. Whether similar stimulation is produced by a fluctuating moisture regime does not seem to have been studied but it is not unreasonable to expect that microbial activity would not be the same as in a system maintained at a constant water status.

A further aspect, not usually reproduced in the laboratory, concerns fluctuations in oxygen tension and the occurrence of anaerobic microsites which are known to occur in the field (Haider, 1983). This could effect rates and pathways of dissipation as these are known to be different under anaerobic than aerobic conditions for several compounds including cypermethrin (Roberts and Standen, 1977), parathion (Sethunathan and Yoshida, 1973; Munnecke and Hsie, 1976) and the dinitroaniline herbicides (Probst et. al., 1975).

Finally, laboratory experiments are constrained by the decline in microbial activity already mentioned. This is important, not only for relatively recalcitrant molecules, but also for studies of the long-term behaviour of pesticide transformation products such as "bound" residues. In these cases, the validity of orthodox laboratory studies must surely be questionable.

Experiments to assess mobility

The rationale for using adsorption/desorption measurements, soil TLC and leaching experiments in columns of soil to assess the mobility of a pesticide in the field is that the soil-water system may be considered as a type of partition chromatography. However, there are now numerous examples (e.g. Graham-Bryce et. al., 1982; Stork et. al., 1990 to show that such laboratory estimates bear almost no relation to what is observed in the field.

The reasons for this are clear. The most important are:

1. Sorption by soil is not a linear, equlibrium, reversible process (even in the laboratory).

2. Field soil is heterogeneous and does not resemble a chromatographic stationary phase with respect either to the partitioning of solutes between mobile and stationary phases or to water movement, because there are preferential flow paths (cracks, worm holes etc) and spatial variability in hydraulic properties.

3. Water movement through the soil does not resemble that of a chromatographic solvent because of soil heterogeneity (as stated in 2. above) and during the growing season movement is largely upwards because of evapotranspiration.

Rao et. al. (1988) and Wagenet and Rao (1990) discuss these issues in detail.

In addition, most laboratory soil leaching column protocols use unrealistically high rates of water application and, partly as a consequence, take a relatively short time so that dissipation processes do not occur significantly.

Field experiments

The foregoing sections are not intended to be an exhaustive critique of laboratory methods for assessing the fate and behaviour of pesticides in the soil but it is hoped that they are sufficient to illustrate the major points. They show that it is hardly surprising that registration authorities are unlikely to approve new compounds on the basis of laboratory data alone. However, the full-scale field experimentation that is therefore necessary brings its own problems and limitations.

Firstly, it is scarcely possible to control most of the environmental and edaphic variables in the field. To a limited degree precipitation may be supplemented by irrigation or reduced with shelters and light may be reduced with shading devices but environmental variables cannot really be controlled in a defined way. This means that interactions between soil type and climate cannot be studied with incremental variations except by comparing results at the same site from different

years or seasons and, to some extent, by comparing different sites in the same climate zone.

Secondly, not only the weather but also soil is variable. This variability includes the variations between soils, which can to some extent be quantified in pedological terms, and also variability within fields or even smaller units (Bunte, 1991). Thus Beckett and Webster (1971) suggested that coefficients of variation for measurements of soil properties in individual samples taken within an area of 0.1 ha are of the order of 10-40 %. Similar variations for pesticide persistence in samples incubated in the laboratory have been reported by Walker and Brown (1983) and Rao and Wagenet(1985), while Taylor et. al. (1971) found larger cvs for the distribution of dieldrin residues in the field. The situation is further complicated because many properties, notably those related to water movement, do not follow a normal (Gaussian) distribution (Biggar and Nielsen, 1976). Therefore the possibilities of using geostatistical methods are under active consideration (Rao and Wagenet, 1985).

Further discussion of these issues is scarcely relevent here; the main point is that to obtain reliable estimates of pesticide behaviour in the field requires very high replication at many sites representing different soil and climate conditions. Thus is time consuming, particularly because results for at least two years from any one site is normally the minimum requirement, and expensive.

There are further restrictions on field studies for reasons of public and environmental safety. Important among these is the prohibition in many countries of the use of radioactive isotopes.

Lysimeter systems

Lysimeters "can be useful models to study the fate of pesticides in soil/plant systems" (FAO Guidelines), stated in the context of leaching studies. As the use of lysimeters becomes more widespread this seems increasingly to be something of an understatement. Lysimeters have a number of features which give them apparent advantages over other experimental systems.

Compared with laboratory techniques they have the advantages that they almost exactly reproduce the environmental conditions that occur in the corresponding field soil (Pütz, 1992) and they do not significantly perturb the soil either mechanically or microbiologically. In addition it is possible to grow crops and carry out cultivations in line with agricultural practice and they can be maintained for many years (Führ et al., 1991). The results integrate the processes that are normally measured separately in the laboratory. Some of the problems of field experimentation can be at least reduced in that soil monoliths from different sources can be grouped at the same site so it is possible to expose soils to different climates. It is usually easier to install equipment to monitor

environmental parameters at a lysimeter station than it is in the field, particularly when a large number of field sites is involved. There is also no restriction on using radioisotopes.

Starting in 1972, the Institute of Radioagronomy of the Nuclear Research Center Jülich GmbH has developed, in close cooperation with pesticide scientists from the Bayer AG Leverkusen, a lysimeter agroecosystem approach (Führ et al., 1991). On the basis of experiments with approximately 50 ^{14}C-labelled pesticides it has been demonstrated that it is possible:

- To quantify overall residues in plants, soil and percolate ("drainage water") and bound, (non-extracted) residues in plants and soil.
- To integrate degradation and leaching studies (including aged residues) and obtain a more realistic assessment that can derived from laboratory studies.
- To define detailed studies of degradation, sorption, release and the availability of residues to untreated rotational crops.
- To obtain information on translocation of aged residues in the topsoil and, with sufficient high specific labelling, also on realistic, extremely low, concentrations in the subsoil.
- To use the information obtained to improve the interpretation of field ecotoxicological studies.
- To validate pesticide transport and degradation models.

Their major disadvantages are expense (though to get the same data from field studies would probably be more expensive even if it were possible) and the fact that environmental parameters can be monitored quite accurately but cannot be very well controlled. It is also not yet clear how well lysimeters will be able to reflect field variablity. However, taking an optimistic view, it is quite conceivable that a well conducted series of lysimeter studies could answer almost all of the questions that must be answered for registration purposes with regard to the fate and mobility of pesticides. That includes those concerned with dissipation pathways and rates as well as mobility, which seems to account for most current regulatory interest in lysimeters. If such development could be achieved, lysimeter studies would be the core source of registration data, supplemented from laboratory and field studies where necessary to resolve particular uncertainties.

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3.
Experimental approaches to Lysimeter Studies: Description of Systems

3. EXPERIMENTAL APPROACHES TO LYSIMETER STUDIES: DESCRIPTION OF SYSTEMS

THE LYSIMETER STATION AT THE INSTITUTE OF RADIOAGRONOMY OF THE RESEARCH CENTRE JÜLICH GMBH (KFA), GERMANY.

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ABSTRACT

A lysimeter system is described in which the fate and long-term behaviour of pesticides in the agroecosystem can be investigated with the application of ^{14}C-labelled active ingredients. The lysimeter units in use now consist of a square or round cylindrical casing, filled with an undisturbed soil monolith. The casing, which stands in a rack with a perforated bottom, is inserted in an absolutely watertight container embedded in the ground of the lysimeter station. All equipment is made from stainless steel. The depth of the monolith is 110 cm, the experimental area of the lysimeters amounts to 0.5 and 1.0 m^2, respectively.

Two different soil types have been used: a clayey silt (orthic luvisol) and a silty sand (gleyic cambisol). All cultivation measures (crop rotation, soil tillage, fertilization and plant protection) are performed in accordance to agricultural practice. Within the soil monolith, temperature, humidity and the migration of water are recorded. A windtunnel device standing over the area of a 0.5 m^2 lysimeter enables direct measurement of pesticide volatilization.

INTRODUCTION

A complete elucidation of the fate and long-term behaviour of pesticides in the soil-plant system, which is controlled by numerous environmental parameters, is only possible using labelling of the active ingredients with the radioactive carbon isotope ^{14}C. This labelling enables, apart from a considerable lowering of the detection limits, the analysis of total residues in plants, in different soil layers, in the leachate, and above all the quantification of the residues persisting in soil and plants in a bound form, i.e. not extractable, and therefore not analytically detectable. For radiation protection reasons radioactively labelled pesticides cannot be applied in the open field in most countries. However, investigations on the long-term behaviour of pesticides have to be carried out

under conditions as close to agricultural practice as possible, if the results are to be realistic. Only lysimeters comply with the dual requirements of safety and realism (Brumhard, 1991; Führ et al., 1976; Führ, 1977; Führ, 1984; Führ, 1985; Führ et al., 1989; Führ et al., 1991; Kubiak, 1986, Mittelstaedt & Führ, 1977; Mittelstaedt & Führ, 1981; Steffens et al., 1990, Pütz, 1992).

DEVELOPMENT OF THE JÜLICH LYSIMETER SYSTEM DURING THE LAST 20 YEARS

Since 1971 the Institute of Radioagronomy of the Research Center Jülich GmbH (KFA) has been using lysimeters, that are microplots of the agricultural ecosystem, to study the fate of ^{14}C-labelled pesticides and radionuclides in the soil-plant system under conditions close to those in practical agriculture. Initially the residue situation and metabolism in plants and in the plough layer were the major interests. The first lysimeters were rectangular containers made from polypropylene with side walls 50 cm high and a surface area of 1 m^2 (Fig. 1).

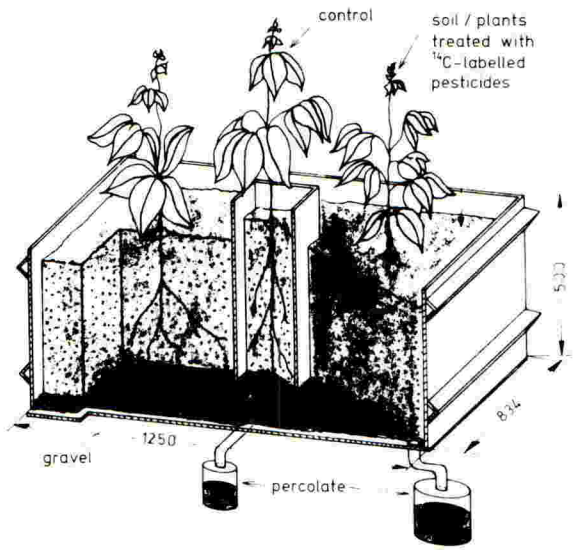

Figure 1: Section of an above ground lysimeter (1 m^2) filled with soil from the plough layer (dimensions in mm).

These lysimeters were filled to a depth of 45 cm with soil from the plough layer (0-35 cm) assuming, that all essential processes responsible for the fate of a chemical compound in the soil take place preferentially in the tilled layer. In the middle of the lysimeter area a small container (20 x 20 x 50 cm) was installed as control area.
At the outside the walls of the lysimeter were insulated with rockwool covered by a shield made from stainless steel to protect the soil against sudden temperature changes (Fig. 2).

The disadvantage of this system was that only soil from the plough layer and no subsoil was included and that the soil depth was too shallow, so the water regime was not realistic and additional irrigation during summer was necessary.

In 1974 a new lysimeter system was developed: cylindrical or square containers made from stainless steel, 60 cm high,

open at the top and at the bottom, with an area of 0.25 m^2 (Fig. 3).

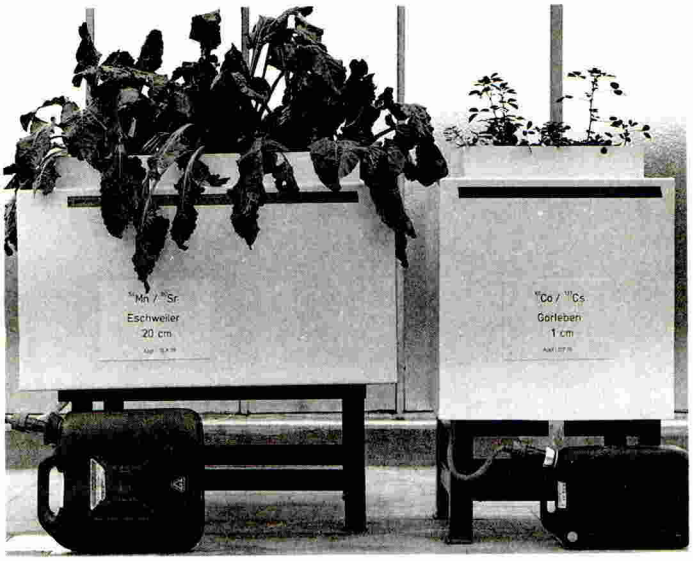

Figure 2: Lysimeters ready for use, filled with soil from the plough layer (left) or an undisturbed soil monolith (right).

These containers were pressed into an arable soil to a depth of 55 cm, thus gaining undisturbed monoliths of the soil profile with plough layer and subsoil. After filling, the lysimeters were set into flat containers made from stainless steel, filled with 5 cm of gravel to facilitate drainage and having an outlet to collect the water, which percolated through the soil column. Again they were insulated and covered by a shield as in the earlier system (Fig. 2). The experimental area was still relatively small, especially for plants like sugar beet or maize, and as the soil monolith was short, additional irrigation was still required.

Therefore, new lysimeters were constructed based on the same system but with larger dimensions. They contained a soil monolith 85 cm deep with a surface area of 0.5 m^2 but otherwise were prepared as described above. These lysimeters (Fig. 4) gave results which where closer to agricultural practice (Kubiak, 1986). However, these lysimeters were still above ground and although they were insulated, the soil monolith was more sensitive to temperature changes than field soil.

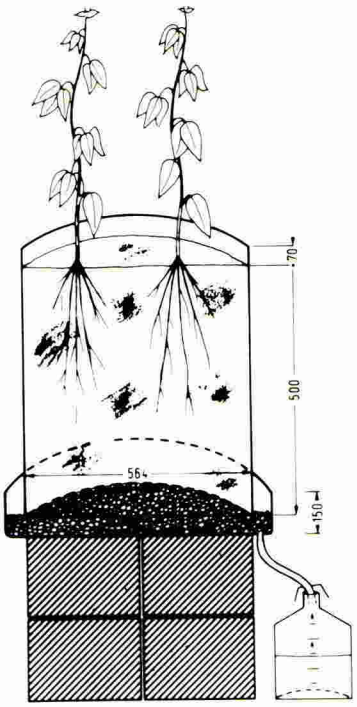

Figure 3: Section of an above ground lysimeter (0.25 m^2) filled with an undisturbed soil monolith (dimensions in mm).

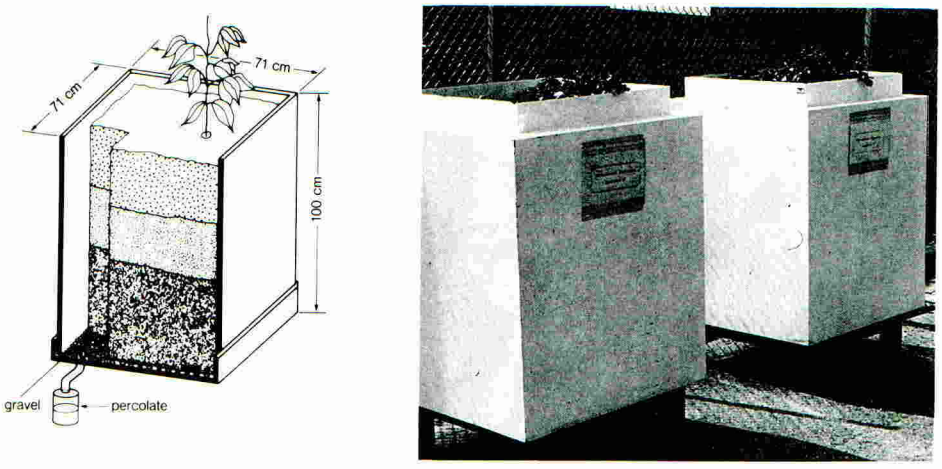

Figure 4: Section of an above ground lysimeter (0.5 m^2) filled with an undisturbed soil monolith (on the left) and lysimeters ready for use (on the right).

The annual mean temperature measured in the soil monoliths was 1-2°C higher than that in a comparable agricultural soil in the field. This might influence especially the biological activity and consequently the decomposition of organic matter, plant residues, and pesticides (Anderson, 1985; Kubiak, 1986; Pütz, 1992).

THE LYSIMETER STATION

At the beginning of the eighties, more emphasis was laid on the degradation and migration of pesticides in the soil especially with respect to the contamination of aquifers. In lysimeter experiments this had to be considered (Bergström, 1990; Brumhard, 1991; Führ, 1985; Führ et al., 1989; Führ, et al.,

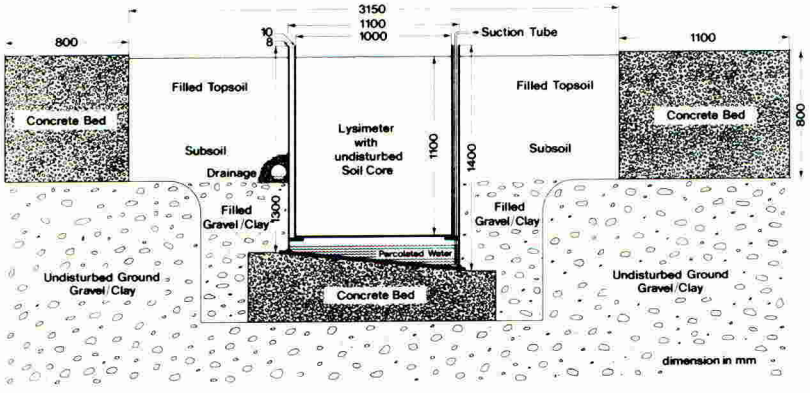

Figure 5: Section of the lysimeter system embedded in the ground (dimensions in mm).

1991; Kubiak, 1986). On the basis of these requirements and of 10 years experience with different types of lysimeters, a lysimeter station was designed and constructed, which allows experiments to be performed, closely reproducing good agricultural practice.

One lysimeter unit is composed of an absolutely watertight square or round container embedded permanently in the ground, in which is inserted a square or round casing keeping the undisturbed soil monolith and standing in a rack open at one side with a perforated bottom having a cutting edge at the front. All this equipment is made from stainless steel. In Fig. 5 a section of the lysimeter installation is shown. The lysimeter unit is placed on a concrete bed and surrounded by topsoil as control area. The filled lysimeter casing stands in the container on 4 arms fastened to the walls at a depth of 120 cm. The container is 130-140 cm deep, so that there is ample space available below the lysimeter to collect the water percolated through the soil monolith. This water is sampled via a suction tube inserted into a pipe which is fixed to the higher wall of the container.

Figure 6: The lysimeter station at the Institute of Radioagronomy

The lysimeters have effective areas of 0.5 (square) and 1 m^2 (square and round),. The radioactive experiment is embedded in a control plot cultivated with the same crops. 50 lysimeters (20 of 0.5 and 30 of 1.0 m^2 surface area), distributed in 10 beds of 5 lysimeters each (Fig. 6), are located in an enclosed open-air area of approx. 2500 m^2. The radioactivity licensed for the application of ^{14}C labelled pesticides amounts to up to 296 MBq/m^2 per lysimeter.

FILLING OF THE LYSIMETERS

Much attention has to be given to the filling of lysimeters in order to create conditions representative of the actual field situation. It is certainly easier to fill lysimeters with soil from disturbed layers than with undisturbed soil monoliths. However, considerable differences in the water movement result between the soils collected with

these two techniques. Therefore, undisturbed soil is a requirement for studying pesticide mobility (Bergström, 1987; Cassel et al., 1974; Führ et al., 1991; Pütz, 1992).

To collect an undisturbed soil monolith, the lysimeter casing is covered at the top with a steel plate, 30 mm thick. At the bottom, the walls of the casing (8-10 mm thick) have sharpened edges for cutting the soil. The casing is pressed or rammed into the soil 110 cm deep by the shovel of an excavator (Fig. 7).

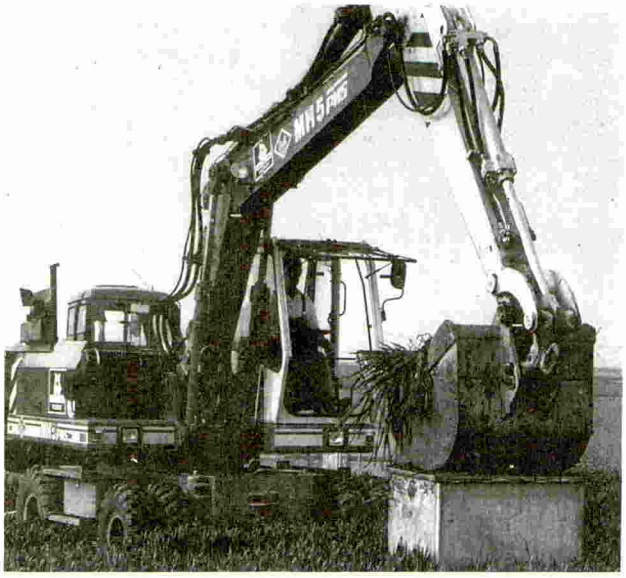

Figure 7: Filling of a lysimeter with an undisturbed soil monolith

This technique guarantees that the soil monolith is pressed close to the walls of the casing and that there are no gaps between the walls and the soil. This is very important when studying the movement of pesticides in the soil. After the casing is pressed into the soil, the surrounding soil is removed and the bottom of the rack is pushed under the casing cutting the soil with the sharpened edge at the front of the bottom (Fig. 7). Then the lysimeter casing with the undisturbed soil monolith standing in the rack is lifted from the hole and transported to the lysimeter station. There the lysimeter casings are inserted into the containers which are permanently installed in the ground (Fig. 8). With this technique up to 15 lysimeters can be filled per day (9 hours).

SOIL SELECTION

In principle any soil with a deep profile can be used to study the behaviour of pesticides. However it will be very difficult, if not impossible, to collect undisturbed monoliths from heavy clays and stony soils using the technique described above.

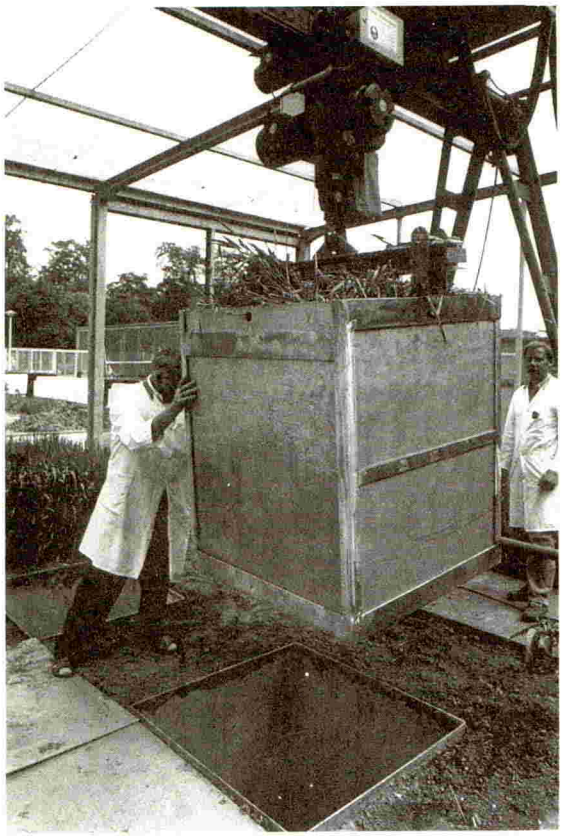

Figure 8: Insertion of a lysimeter casing into the container embedded in the ground of the lysimeter station.

At the Institute of Radioagronomy two soil types are used which are representative of agricultural soils in Germany: 1. a clayey silt (orthic luvisol = Parabraunerde) and 2. a silty sand (gleyic cambisol = schwach pseudovergleyte saure Braunerde). The second soil type has a higher water permeability and is included in the experimental programme, particularly to study the leaching tendency of pesticides. This soil type is in compliance with the German guidelines for the testing of agrochemicals (BBA Guidline IV, 4-3). The physical and chemical properties of these two soil types are presented in Table 1 and 2.

APPLICATION OF THE ^{14}C-LABELLED PESTICIDE

In agricultural practice, spraying solutions of pesticides are assumed to be applied evenly. On microplots like lysimeters with an area of 0.5-1.0 m^2 a homogeneous spraying is rather difficult. However a homogeneous distribution of a pesticide solution on plants and soil is a prerequisite in lysimeter experiments for sampling reasons. Realistic rates of pesticides and spray solution volumes (20-40 ml/m^2) as usual in agricultural practice should be applied to give results transferable to the field situation. Two different spraying

Table 1: Chemical and physical properties of the clayey silt (orthic luvisol = Parabraunerde), origin Merzenhausen

Horizon	Ap	A_l	B_{t1}	B_{t2}	B_{t3}
Depth, cm	0-39	39-55	55-77	77-98	98-119
pH-value (KCl)	7.2	6.9	6.8	6.7	6.5
CAC (meq/100 g)	11.4	12.2	12.2	10.5	11.0
S-value (meq/100 g)	11.5	12.0	11.5	10.7	11.1
C_{org} %	1.1	0.4	0.3	0.3	0.3
Total N %	0.11	0.06	0.05	0.04	0.04
K_2O (mg/100 g)	33.0	30.0	14.0	5.0	6.0
$CaCl_3$ %	1.0	0.8	0.8	1.0	0.8
Total sand %	6.4	1.0	0.1	0.8	0.7
Total silt %	78.2	77.1	73.4	74.1	72.7
Clay %	15.4	21.9	26.5	25.1	26.6

Table 2: Chemical and physical properties of the silty sand (gleyic cambisol = schwach pseudovergleyte saure Braunerde), origin Kaldenkirchen

Horizon	Ap	B_{v1}	B_{v2}	B_{v3}
Depth, cm	0-33	33-55	55-70	70-120
pH-value ($CaCl_2$)	5.52	5.74	5.80	5.86
S-value (meq/100 g)	2.8	1.5	1.3	0.5
T-value (meq/100 g)	11.0	11.4	11.5	11.8
C_{org} %	1.0	0.2	0.2	0.1
Total N %	0.01	0.01	0.01	0.01
K_2O (meq/100 g)	8.0	4.0	3.0	1.0
$CaCO_3$ %	0.6	0.1	0.2	0.2
Total sand %	75.2	70.3	76.8	89.9
Total silt %	21.6	25.2	20.1	8.8
Clay %	3.2	4.5	3.1	1.3

techniques are used: a hand operated garden sprayer and a special automatic spraying apparatus with nozzles used in agriucltural practice (Fig. 9). Before spraying the lysimeter area is surrounded by thin aluminium plates covered with a tin foil in order to avoid a contamination of the surrounding area and to control - for balance purposes - the amount of the ^{14}C-labelled pesticide, not reaching the lysimeter area. Severeal treatments have shown, that up to 20 % of the applied pesticide does not reach the xperimental area (Mittelstaedt et al., 1992). This has to be taken into account when planning the application of definite rates of a certain pesticide. This problem does not occur in experiments, where seeds are sown treated with a ^{14}C-labelled pesticide. (Schneider, 1988; Steffens et al., 1982; Stein-Dönecke, 1992; Thielert et al., 1986;).

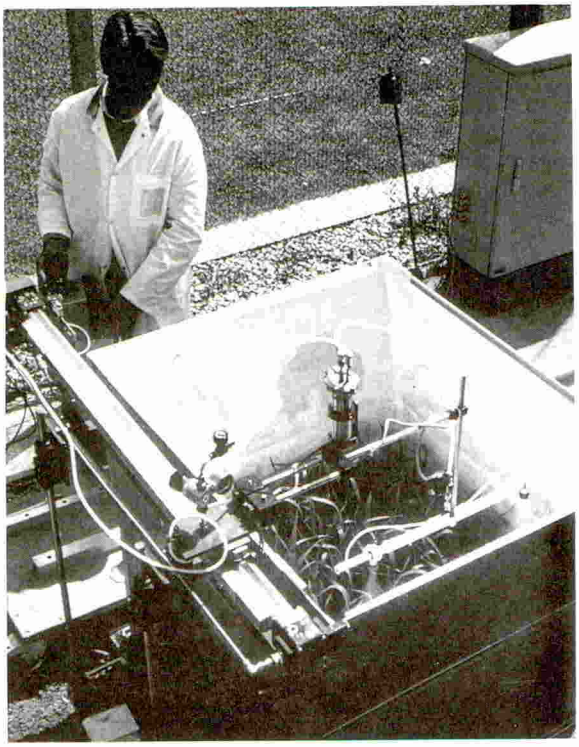

Figure 9: Automatic spraying apparatus for applying ^{14}C-labelled pesticides in lysimeter experiments.

TREATMENT OF THE LYSIMETERS

The lysimeter experiment as far as possible duplicates good agricultural practice. Ploughing of the soil is simulated by digging with a spade 30 cm deep and appropriate additional cultivation is performed to produce a seed bed. Typical crop rotations are used, for example on the clayey silt, sugar beet followed by wheat and barley or potatoes. The same rotation can be used on the silty sand or an alternative consisting of maize followed by wheat, potatoes and sugar beet. Rye, oats, rape and vegetable crops like carrots, spinach, bush beans and lettuce are sometimes included in these rotations, but that crop treated with a ^{14}C-labelled pesticide is always the first one in the rotation. If appropriate, intermediate crops like mustard plants, phacelia or clover are also grown.

Base fertilization, appropriate to the crops, with a complete fertilizer containing N, P_2O_5, K_2O and MgO and if

neccessary liming is performed before sowing or in early spring. During the vegetation period additional nitrogen split into 2-4 applications is given. In order to control infestations of weeds, fungal pests and insects within the lysimeter and the surroundings herbicides, fungicides and insecticides are applied as necessary. All these cultivation measures - fertilization and pest control - reproduce those applied on the field plot, from where the soil monoliths were taken. A meteorological station registers air temperature and humidity, precipitation and wind velocity. Temperature and water content in the soil are recorded too. In some experiments the migration and use of water in the soil is monitored by applying water labelled with the stable isotope ^{18}O (Förstel et al., 1991). Details are described in chapter 5 (Pütz et al., 1992).

In addition to natural annual precipitation of about 650 mm at the region of Jülich a further 150 mm of water have to be given to reach the 800 mm minimum for each lysimeter as required by BBA Guidline IV, 4-3. This is done by adding the deficit from one month during the following month using an automatic sprinkler.

MEASUREMENT OF PESTICIDE VOLATILIZATION FROM LYSIMETERS

During the past only three compartments of the agricultural ecosystem (soil, plants and percolate) were analysed to study the fate of pesticides. Recently considerable attention has been paid to another aspect: volatilization. Since 1992 the BBA requires data on the volatilization behaviour of pesticides (Guideline IV, 6-1) for registration purposes.

In the Institute of Radioagronomy an apparatus has been developed as an experimental approach to measure pesticide volatilization and mineralization under field conditions, using the lysimeter system. A wind tunnel made of glass has been installed over a 0.5 m^2-lysimeter (Fig. 10) with a blowing/airconditioning unit at one side and a trapping system at the other side to get a representative aliquot of the airstream for the analysis of ^{14}C-labelled compounds. To minimize analytical problems the air passing through the tunnel is free of dust and organic pollutants. The top is variable in height and the wind speed is kept constant (1 m/s) in the free space of 30 cm above the unplanted soil or the vegetation covering the lysimeter. Without changing the air humidity, the temperature situation in the tunnel is permanently adjusted to that outside. Because of the glass construction long term experiments can be conducted.

This development will increase the accuracy of lysimeter balance studies because losses of unchanged ingredient, metabolites or carbon dioxide to the atmosphere can be measured. It is well known that it is difficult to transfer data from the laboratory to the field situation. This system, standing between field and laboratory experiments, will help to validate laboratory systems (BBA Guideline IV, 6-1) which conduct volatilization experiments only under artificial conditions.

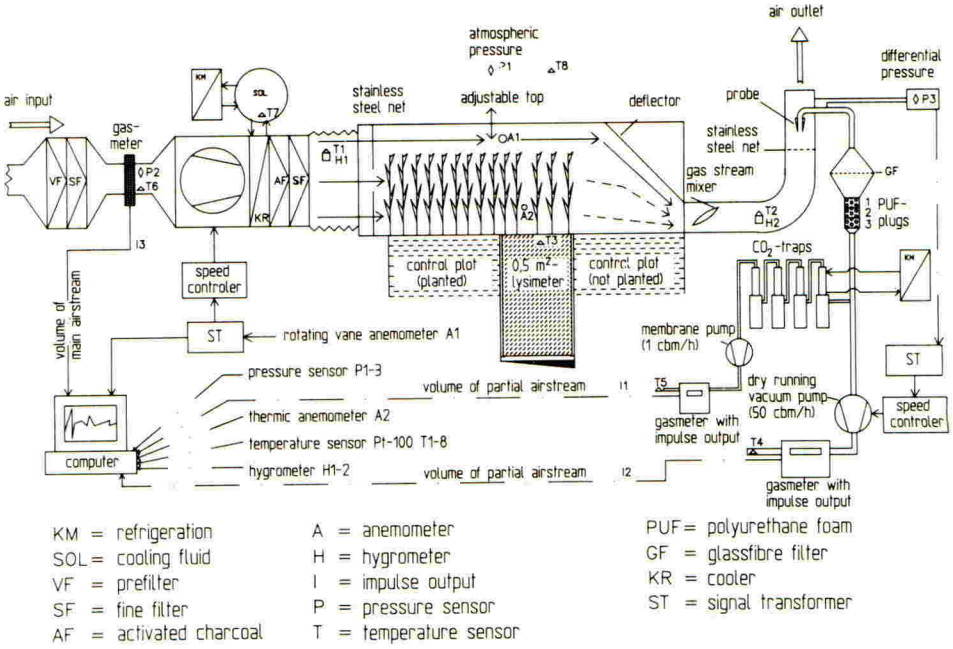

Figure 10: Windtunnel for direct measurement of pesticide volatilization in lysimeter experiments.

CONCLUSIONS

The special advantages of experiments with ^{14}C-labelled pesticides using this lysimeter system are:

- ^{14}C-labelled pesticides can be used in conditions close to agricultural practice
- The behaviour of pesticides can be studied over several growing seasons.
- Mass balances can be drawn up considering all processes of dissipation including volatilization.
- Sufficient soil is available for detailed studies of specific processes (degradation, availability, formation of non-extractable (bound) residues in different soil layers).
- The water percolating through the soil monolith can be collected and investigated for ^{14}C-labelled substances.
- Uptake of pesticides by plants and internal distribution can be studied with autoradiography (see chapter 6, Führ et al., 1992).

The German Federal Agency of Biology (BBA, 1990) has accepted this lysimeter system to study especially the leaching behaviour of pesticides out of the plough layer into the rooted subsoil zone.

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OUTDOOR LYSIMETER EXPERIMENTS: PROCEDURE AND TEST SYSTEM

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ABSTRACT

A method for the collection of undisturbed soil cores (profile depths of 1.0 to 1.5 m, surface area of 1 m^2) from the field and the outdoor lysimeter facitity are described.

The lysimeter experiments are performed with ^{14}C-labelled test substances. For an experimental period of at least two years the lysimeters are cultivated according to the agricultural practice, and the leachate is collected in a container at the bottom and periodically analysed. During the study the sampling of soil cores is restricted to the tillage layer. At the end of the study the soil monolith is divided into 10 cm horizontal segments using a special patented technique and analysed in detail.

Replicate lysimeters give similar results in respect to annual leachate volumes and concentrations of test substance and metabolites in the leachate.

INTRODUCTION

Since 1986 at the Fraunhofer-Institut für Umweltchemie und Ökotoxikologie the fate of pesticides has been studied using lysimeters with undisturbed soil cores. The outdoor lysimeter plant is situated on the ground of the institute in Schmallenberg (Germany, State of North-Rhine-Westphalia) and comprises 48 lysimeters, each with an area of 1 m^2 and profile depths of 1.0 to 1.5 m. Several national and international companies are running lysimeter experiments using the patented equipment (see description below), which has been developed at the institute.

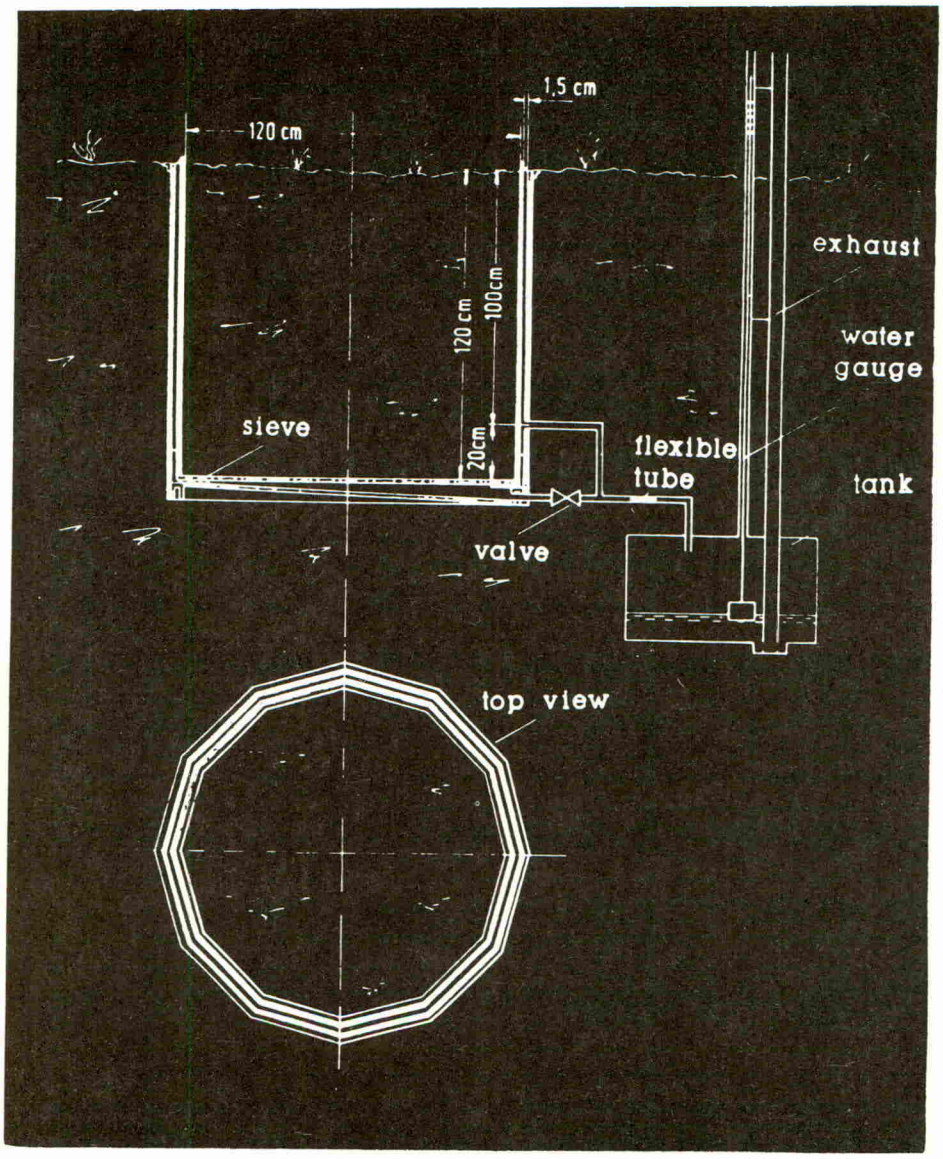
DESCRIPTION OF THE LYSIMETER EQUIPMENT AND THE LYSIMETER PLANT

Figure 1 shows a scheme of the lysimeter. The equipment is made of stainless steel, a material with a high stability but no tendency to adsorb organic material. The twelve sided shape of the lysimeter gives the container a high stability. It consists of an inner and an outer container of 1.0 to 1.5 column length and 1 m^2 surface area. The outer container has two outlets for the leachate. A groundwater level can be simulated by closing the lower outlet and using the upper one. The leachate is collected in a separate tank connected with the container by a flexible tube. Water leaching through the

lysimeter is collected from this tank into a sampling bottle.

The lysimeters are embedded in the earth. To prevent animals from entering the lysimeter field, the whole area is surrounded and covered by a wire-netting fence.

FIGURE 1. The Schmallenberg-Lysimeter

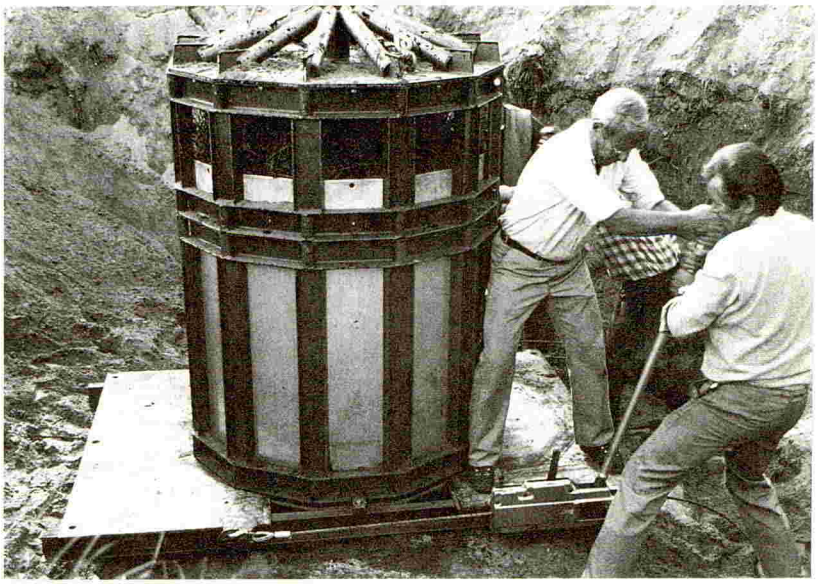


COLLECTION OF THE SOIL MONOLITHS FROM THE FIELD

Using a technique developed at this institute (Spiekermann, 1990) more than 70 undisturbed soil monoliths of various soil types have been collected so far, including those with stony subsoils.

To collect soil cores from the field the inner container is fixed in a driving device with a cutting device at the bottom. The driving device, which prevents the distortion of the container during the collection of the monolith, is pressed down into the soil (approx. 20 - 30 cm in a sandy soil) by a large excavator without any shaking and vibration. The surrounding soil is excavated and the driving device is pressed down a further 20 - 30 cm. When filled to a profile depth of 1.0 to 1.5 m, the soil monolith is cut at the bottom of the container (see Figure 2) and the end is covered with two sieve plates of different mesh sizes.

FIGURE 2. Equipment for the collection of the soil monolith from the field



An extremely careful collection of the monolith is the first and basic step in the performance of a valid study. For that reason the soil core has to be cut accurately since any inhomogeneities will cause disturbances in the soil structure and lead to erroneous results.

The inner container with the soil core is transported to the lysimeter plant and installed into the outer one. The remaining small space between the inner and outer container is sealed by silicone paste.

PERFORMANCE OF LYSIMETER STUDIES

Prior to the application of a pesticide the lysimeter is surrounded by a plastic cage to avoid contaminations of the adjoining area. The ^{14}C-labelled test substance (in an aqueous formulation or organic solution) is automatically sprayed under pressure (2 to 4 bar) onto the surface of the lysimeter (Stork et al., 1990). For the application a hollow cone nozzle ("ALBUS ATR rot"; France) is used. The volume rates of the applied solution range from 20 to 2000 ml, but usually do not exceed 100 ml. After the treatment the plastic cage is removed. The radioactivity of the plastic foil is determined so that the exact amount of the pesticide on the lysimeter can be established.

Usually lysimeter experiments are run in duplicate. The two lysimeters and the surrounding area of approximately 15 m^2 are planted and treated in the same way to avoid edge effects and to achieve a microclimate comparable to field conditions.

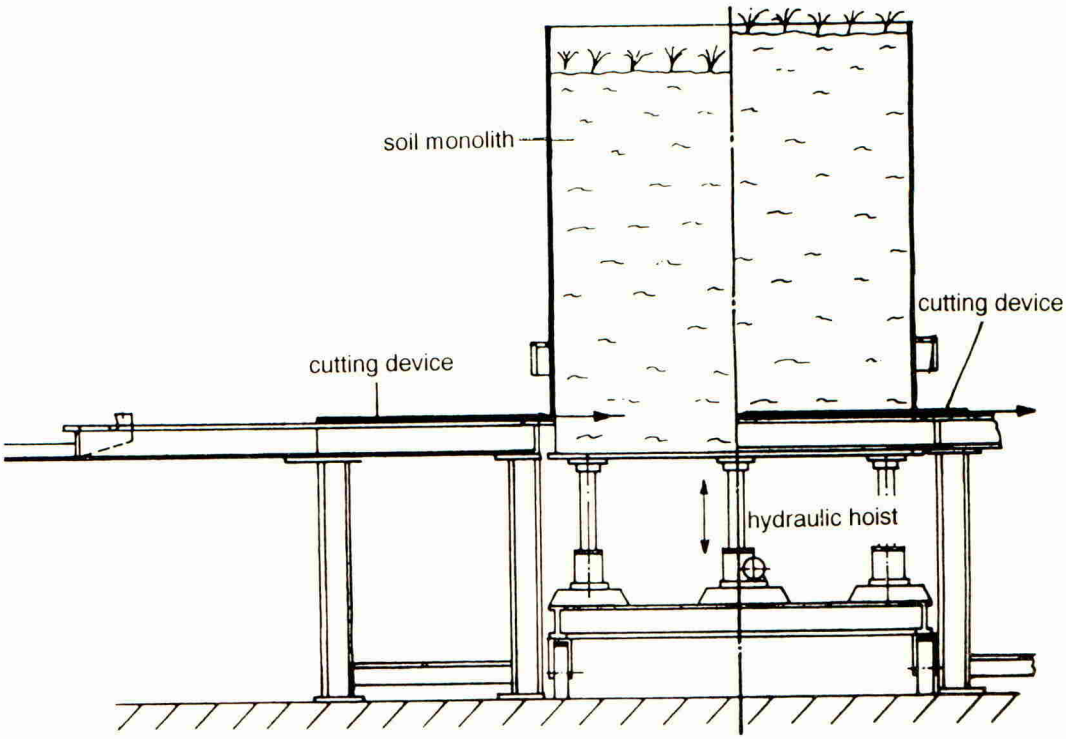
The studies usually continue for at least two years with periodic analyses of the total leachate. The ^{14}C-uptake of the cultivated plants is determined. During the study the sampling of soil cores is restricted to the tillage layer, since refilled soil cores act as drains (Kördel et al., 1991).

The maximum and minimum temperatures of the air and soil at depths of 10, 30 and 60 cm, precipitation, soil moistures at depths of 15, 45, 75, 105 cm, wind speed and direction are recorded daily.

At the lysimeter plant in Schmallenberg the annual precipitation is above 800 mm per year, which is required as realistic worst case for Germany (Anonymous, 1990). No supplemental watering, except for vegetables and young crops in a dry period, is needed. Depending on the plants and the weather conditions the total annual leachate volumes range from 300 to 650 l. Most of the leachate is obtained in winter. Due to evapotranspiration normally no leachate occurs during the cropping season.

At the end of the study the soil monolith is divided into 10 cm horizontal segments using a special patented technique (Steinhanses & Kördel, 1990). The lysimeter is put on a table equipped with the cutting device and a hydraulic hoist underneath (see Figure 3). The sieve plates and the cutting device are removed, so that the monolith is standing on the hoist. For cutting each segment the hoist is lowered for 10 cm and the cutting device is closed again.

FIGURE 3. Cutting device for the soil monoliths



Each soil segment has to be described and characterized in detail since the occurrence of macropores, stones, limited disturbances, earthworm channels etc. in the monolith may have influenced the water movement and thus have to be considered when interpreting the results. The soil samples obtained from each segment are extracted and analysed in detail.

The reproducibility of the lysimeters, investigated under the same experimental conditions, is demonstrated by the following examples:

1) Replicate lysimeters have similar annual leachate volumes. Monthly amounts of leachate of five soil monoliths under identical vegetation cover are given in Figure 4. The comparison of the monthly leachate volumes shows that significant differences are only observed for the first samples received after the cropping season in early autumn. This variation could be explained by different water contents of individual lysimeters due to a differing growth of the cultivated plants. Also a preferential water flow through cracks and crevices, formed in a dry period during the cropping season, can play a role (Kördel, et al., in press).

FIGURE 4. Monthly leachate volumes obtained from replicate lysimeters

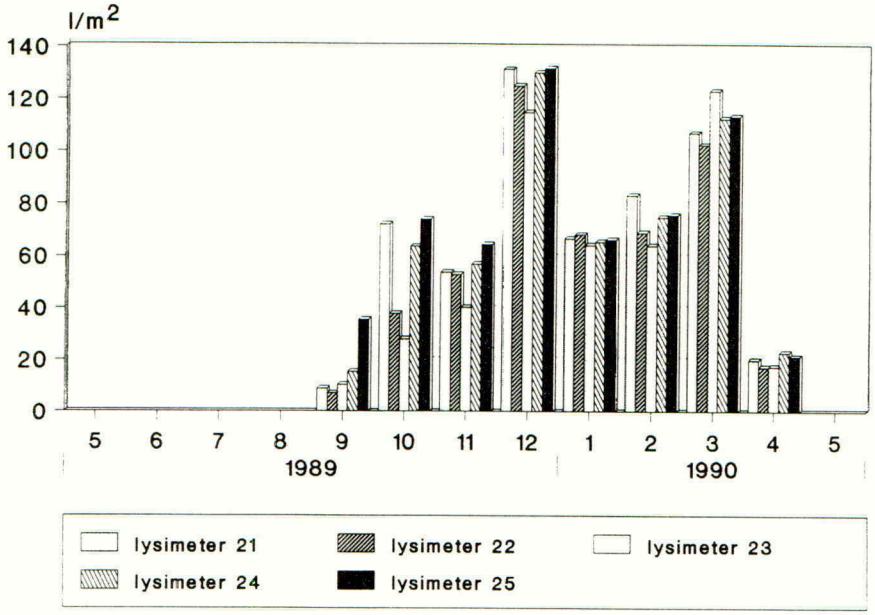
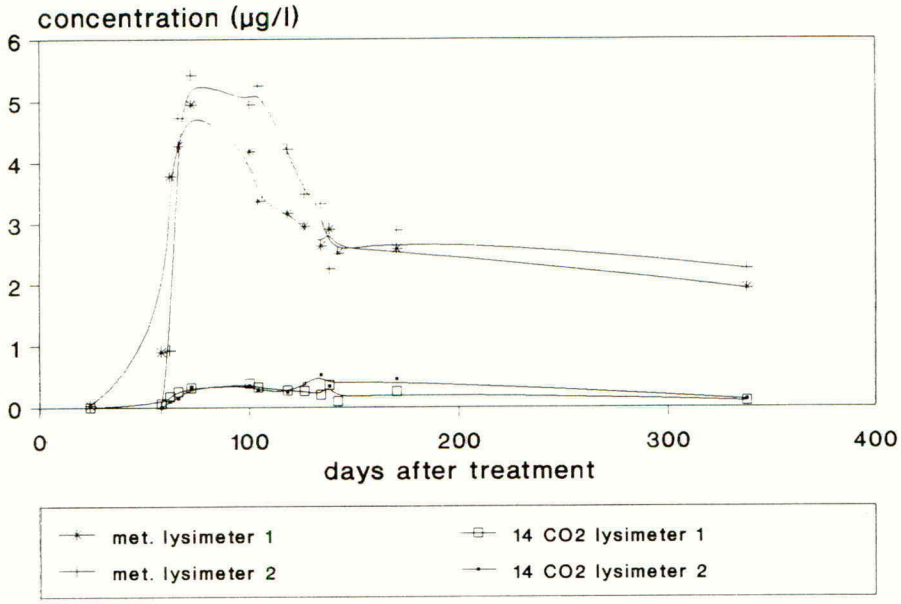


FIGURE 5. Concentration profile of metabolites and $^{14}CO_2$ in the leachate of replicate lysimeters



met. = metabolites

2) The concentration profile of the radioactive material in the leachate of replicate lysimeters is similar. Figure 5 shows the parallelism in the concentration of metabolites and $^{14}CO_2$ detected in the leachate of two lysimeters treated with a herbicide under the same experimental conditions.

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A LYSIMETER SYSTEM TO DETERMINE LEACHING AND VOLATILIZATION OF ^{14}C-LABELED COMPOUNDS

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ABSTRACT

Lysimeters were filled with different soil horizons from natural soils and pressed to the same density as in the field. After application of the ^{14}C-labeled pesticide, small volatilization chambers were placed on the soil. By trapping aliquots of the air which was sucked through the chamber at a speed of 0.2 m/sec, volatile organic ^{14}C-labeled compounds and $^{14}CO_2$ resulting from total degradation of the pesticide could be determined separately. Radioactivity in the leachate was measured every two to four weeks, depending on precipitation.

INTRODUCTION

In the literature various authors describe laboratory model systems for direct and indirect determination of volatilization of pesticides from treated surfaces. The indirect methods estimate the volatility losses by measuring the remaining pesticide concentration in the treated material; with these methods it is not possible to distinguish between losses due to volatilization and losses caused by total degradation of the pesticide. In the direct methods (Starr & Johnson, 1968; Lichtenstein & Schulz, 1970; Gückel et al., 1973; Burt 1974; Que Hee et al., 1975; Kilzer et al., 1979; Spencer et al., 1979; Ferreira & Seiber, 1981; Burkhard & Guth, 1981; Klöpffer et al., 1982; Nash, 1983a, 1983b; Sanders & Seiber, 1983, 1984; Branham et al., 1985; Branham & Wehner 1985; Dörfler et al. 1991), volatilized pesticide is collected from the air using various trapping systems. So far, no method has been reported that allows the direct determination of the volatilization of pesticides from lysimeters. With the system described here, it is feasable to determine, in addition to the leaching, volatilization and biodegradation processes separately.

METHODS

Lysimeter and soil

The round lysimeters (Fig. 1) - with a depth of 1 m and a circumference of 2 m (surface area 0.32 m^2) - were made from stainless steel. A wirecloth and 3 metal plates which had been punched before, resulting in a "hole area" of about 50% of the total lysimeter area in the bottom of the lysimeters, allowed

A = Suction candle

B = Thermometer

C = Tensiometer

D = Thermic Anemometer for wind speed measurements

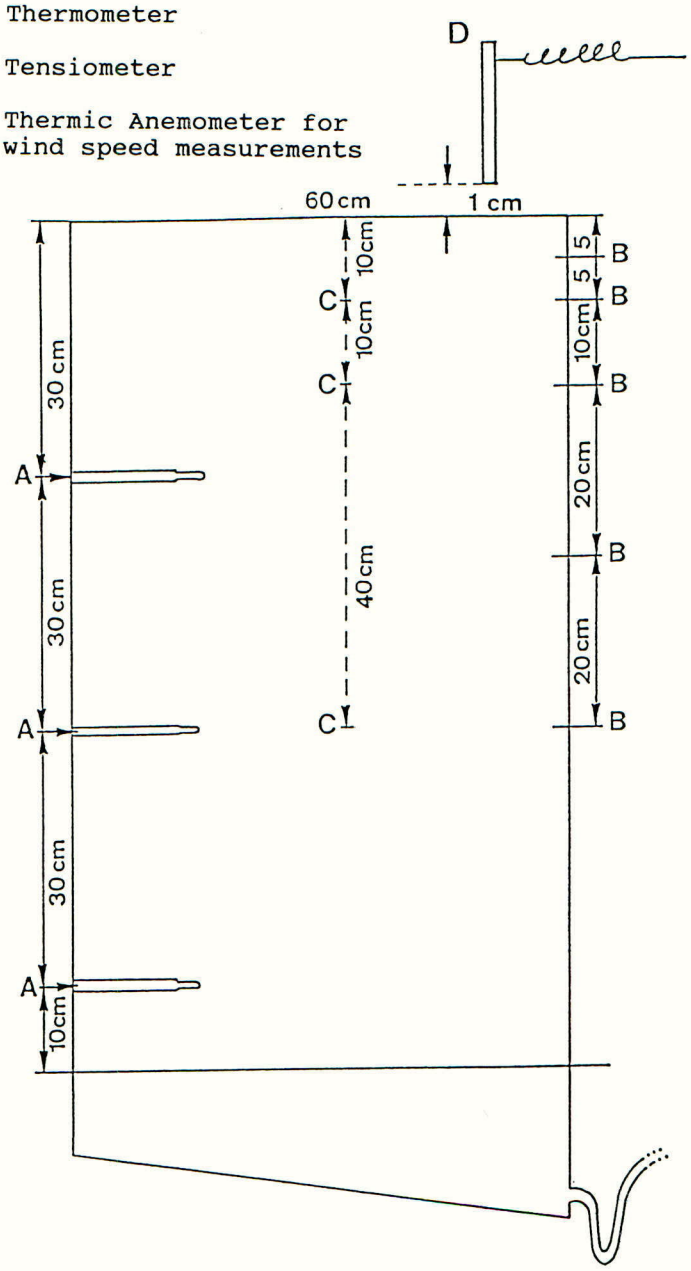

Fig. 1: Lysimeter

the leachate to run out of the soil column.

The soils were taken from different sampling sites ("Neumarkt" and "Segeberger Forst") and each soil horizon was sampled separately (Table 1 and 2). After transport in plastic bags to the lysimeter station they were put into the lysimeters and pressed to the same density as in the natural soils (Table 1 and 2). Soil horizons which had a depth of more than 5 cm were divided (by weight - calculated from the specific density of each soil horizon) into the equivalent of 5 cm layers and then compressed to 5 cm layers in the lysimeter.

The "Neumarkt" soil (Table 1) was a sandy agricultural soil with 85% sand in the upper horizon and nearly 100% sand in the C-horizon; silt (10% - 0%) and clay (5% - 0%) decreased from the upper to the deepest horizon. The pH was between 4.9 and 5.5 from the upper to the deepest horizon and the amount of organic matter decreased from 1.77% in the Ap-horizon to 0.09% in the C-horizon.

Table 1: Soil density and ATP-Content of the soil "Neumarkt".

Soil horizon	Depth (cm)	Soil density (g dry weight/cm^3)	ATP-Content (µg/g dry weight)
A_p	0-28	1.50	0.506
M	28-36	1.76	0.079
fA_h	36-51	1.70	0.060
B_v	51-80	1.53	0.026
C	80-100	1.65	0.013

The "Segeberger Forst" (Table 2) soil was a forest soil ("Podsol"). Therefore the upper 18 cm of the soil had to be taken with a round metal frame to obtain an undisturbed soil core. The other soil horizons were dug out in the same way as described above. In the mineral soil horizons of the forest soil the amount of sand was more than 99%. The amount of organic matter in this soil decreased from about 9.5% in the O_h-soil horizon to about 2% in the B_s-horizon. The pH increased from 3.0 to 4.2 in these horizons.

Table 2: Soil density and ATP-content of the soil "Segeberger Forst".

Soil horizon	Depth (cm)	Soil density (g dry weight/cm^3)	ATP-Content (μg/g dry weight)
O_l O_f	0-6	--	--
O_h	6-10	1.08	1.804
A_h	10-18	1.08	1.804
A_e	18-23	1.52	0.075
B_h, B_s	23-33	0.94	0.212
B_s	33-43	1.53	0.017
B_{vt}	43-100	1.56	0.015

To get information about the water flux in the lysimeters, tensiometers were placed 10, 20 and 60 cm below the soil surface (Fig. 1). Thermometers at depths of 5, 10, 20, 40, and 60 cm (Fig. 1) gave information about the temperature gradient in the soil columns.

Also several suction candles (3 at each depth) were placed at 30, 60 and 90 cm to obtain water samples (Fig. 1).

A water reservoir was placed below the soil column in the lysimeter to collect the leachate for at least 4 weeks. The leachate was sucked by means of a vacuum pump into 5 l glass bottles which were stored in a refrigerator at a temperature of 4°C. Water was collected intermittently every 2 or 4 weeks.

The microbial activity was estimated from the ATP-contents of the different soil horizons (Tab.1 and 2) and in the leachate, determined by the method described by Zelles et al. (1985). Leachate from the Neumarkt soil contained 0.054 μg/l ATP but none was detected in that from the Segeberger soil.

Volatilization chamber

The volatilization chamber (Fig.2), based on the experience of Dörfler et al.(1991), was designed to determine ^{14}C-losses from soil surfaces. The chamber which was made of plexiglass, was 28 cm long, 2 cm high and 8 cm wide. Air was sucked through the chamber at 0.2 m/sec. Wind speed measurements taken 1 cm above the lysimeter soil surface outside the chamber (Fig.3) showed that 0.2 m/sec is a good average value. There was nearly no difference between the wind speed measurements on the lysimeter without plants and lysimeter with maize plants which had reached a height of about 30 cm. In the inlet funnel of the chamber 4 metal sieves were placed to produce a nearly laminar air stream in the chamber. The lower part of the chamber consisted of a metal frame which was pressed into the soil surface to make sure that only

1. lysimeter
2. volatilization chamber
3. air stream splitter
4. air flow meter
5. pump (0.6 kW)
6. viton tube
7. absorption traps for volatile ^{14}C-pesticide
8. absorption traps for ^{14}C-CO_2
9. charcoal filter
10. air flow meter
11. pump
12. air inlet

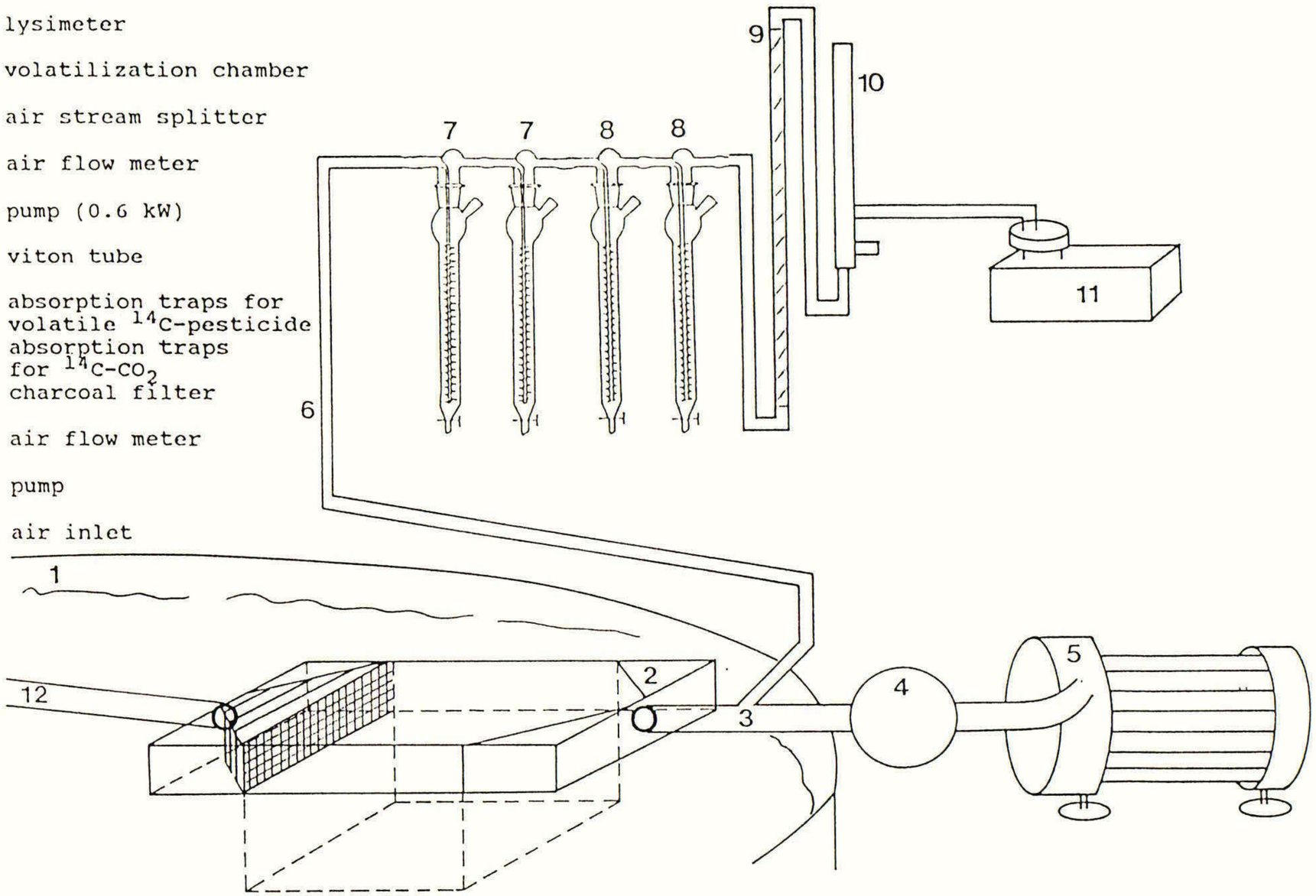

Fig. 2: Volatilization chamber for lysimeters

substances volatilizing from the test area of 20 cm length and 8 cm width were collected in the system.

A small part of the total airstream (0.2%) which passed through the volatilization chamber was taken for the determination of the volatile ^{14}C-labeled compounds. To determine the volatile pesticide, volatile metabolites and $^{14}CO_2$, the air stream fraction was passed through a trapping system consisting of two tubes containing ethyleneglycolmonomethylether to remove volatile pesticide residues and two tubes containing a mixture of Carbosorb and Permafluor (2:3; v:v) to trap ^{14}C-labeled carbon dioxide. At the end of the trapping system there was a charcoal filter, a gas flowmeter and a small membrane pump. The main air stream in the chamber could be determined by a gas flowmeter in front of the large membrane pump. The sampling period lasted to the end of October.

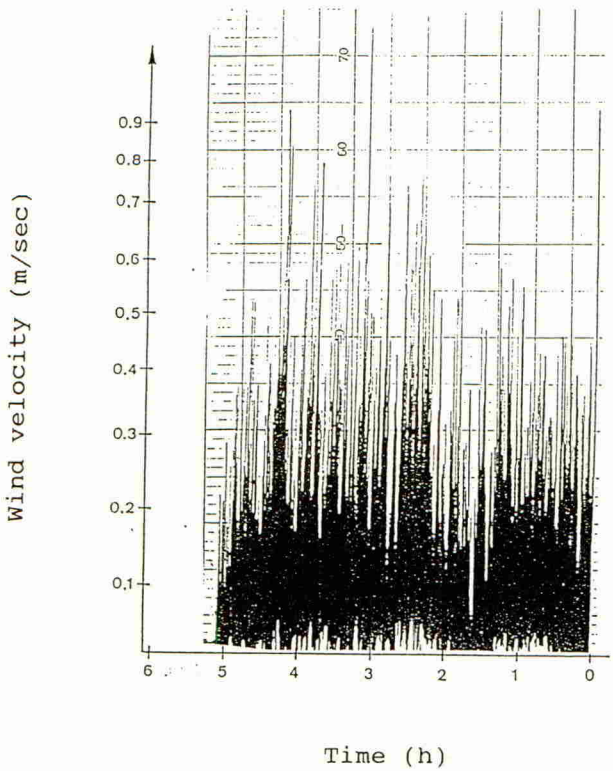

Fig. 3: Wind velocity, 1 cm above the soil surface of the lysimeters (without plants)

In the volatilization chamber the microclimate was different from the climate of the open lysimeter. In order to treat the whole lysimeter surface equally, the volatilization chamber was moved several times (after about 30 days each) to different sections of the soil surface within the same lysimeter.

All tests were carried out in triplicates.

Results are presented in chapter 4.

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THE LYSIMETER SYSTEM IN THE DEPT. OF PHYTOMEDICINE, NEUSTADT, GERMANY

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ABSTRACT

Round lysimeters containing an undisturbed soil core 1.3 m deep with a surface area of 0.8 m2 are described. The application technique allows an exact determination of spraying losses. Investigation of plants, percolate and soil samples provide detailed information on the behaviour of the ^{14}C-labelled compounds under practical outdoor conditions.

THE CONCEPT

The lysimeters used for the studies are circular vessels made of stainless steel. An inner container is filled with an undisturbed soil core with a surface area of 0.8 m^2. A sieve is attached to the bottom to allow for free drainage of the

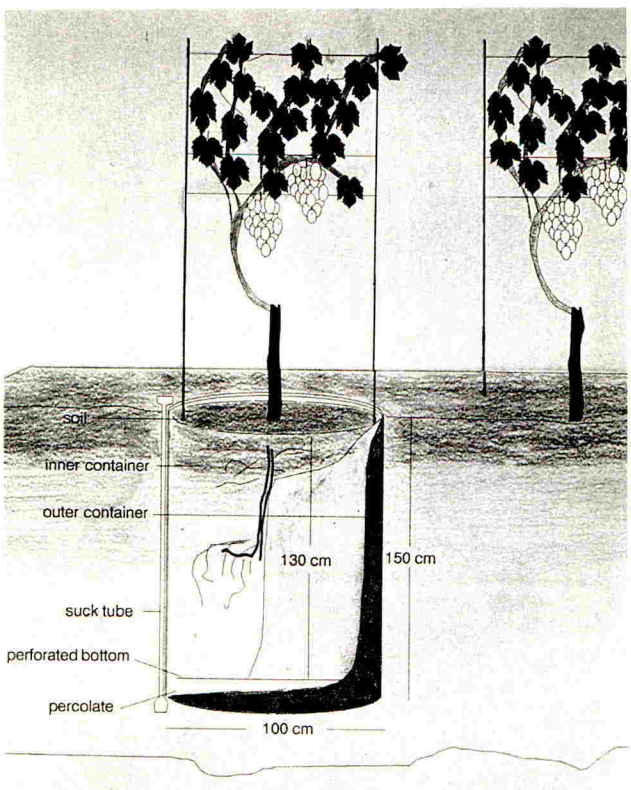

Fig. 1: The lysimeter concept used in Neustadt

percolate, which is collected in an outer container from which it can be drawn off using a tube and a suction pump.

The whole system is embedded in the ground and fixed on a concrete base. The surrounding area is used as a guard plot where the same plants are grown as in the lysimeter. All kinds of crops are used for the studies, however in Neustadt, the vine is frequently used as a test plant, so that some of the lysimeters are planted with one vine, each (Fig. 1).

The lysimeter station consists of 34 lysimeters and is surrounded with a cage to meet the requirements of radiation protection and to avoid any loss of radioactivity caused by animals (for example birds or mice). The distance between the lysimeters is 110 cm or 220 cm. The undisturbed soil cores are 130 cm deep. To obtain them, the inner container is brought to the field and pressed into the ground using an excavator (Fig. 2). Then it is carefully pulled out. If soil moisture is sufficient (10 % for sandy soils and 20 % for clay soils, must be determined before) the soil core breaks even at the bottom of the inner cylinder and a bottom plate drilled with 72 holes, 1.5 cm i.d) covered with a wire mesh is attached.

Fig. 2: How to get an undisturbed soil profile

The soil core is then taken to the lysimeter station and introduced into the outer container already embedded in the ground fixed on a concrete base. The sloping bottom of the outer container leads to the tube so that all percolate can be collected.

APPLICATION TECHNIQUE

A superstructure made of connected metal hoops is used for all spraying operations. It consists of two parts, one 0.5 m high and the other 1.5 m high which can be used alone or in combination (Fig. 3a). For soil application or application to crops at an early stage,the 0.5 m superstructure is used, for application to vine both parts are connected. The superstructure runs flush with the edge of the lysimeter. A tube of plastic foil is fitted round the superstructure and closed at the top.

For application, a hole is cut in the plastic and the radioactive solution is sprayed through it at a pressure of 1.5 bar with a hollow-cone nozzle as used in agricultural practice (AMTP 208). A glass tube containing the spray mixture is placed in a plastic container screwed tightly to the spraying equipment and to the compressed air cylinder used to produce the required pressure (Fig. 3b).

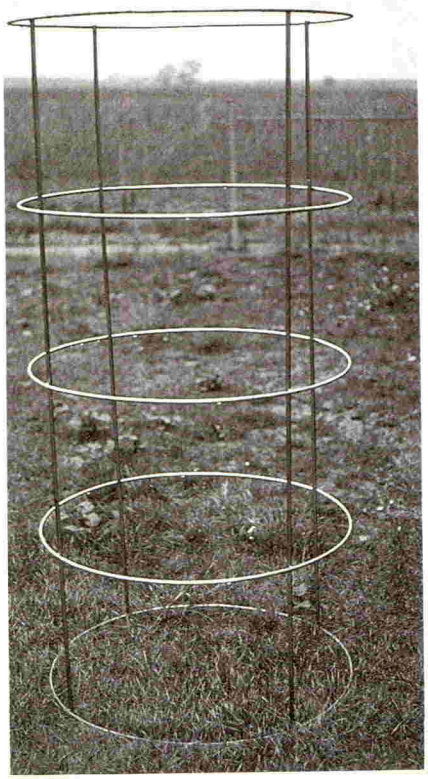

Fig. 3a: Equipment for application - the superstructure

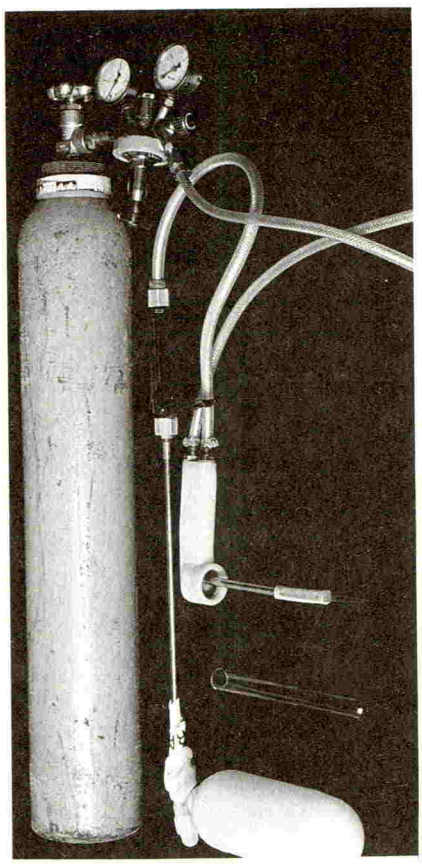

Fig. 3b: Equipment for application - the spraying tools

DETERMINATION OF SPRAYING LOSSES

The spraying losses consist of ^{14}C residues in the storage container, the spraying equipment and on the plastic tube. In order to quantify these losses, the storage container and the spraying equipment are rinsed with suitable solvents after each application, and aliquots are taken to determine the radioactivity. Each of the plastic tubes is immersed in approx. 10 l of a suitable solvent for 48 hours to dissolve all adhering radioactivity. Aliquots of the solvent are then measured. The sum of all losses is deducted from the amount of radioactivity used for spraying and the result is the total amount of ^{14}C applied on the lysimeter. This is the basis of all further calculations.

TREATMENT AND MEASUREMENTS DURING STUDIES

Agricultural practice with respect to application of fertilizers, crop rotation, and soil cultivation is simulated during the studies. Additional plant protection is reduced to a minimum to avoid possible interaction with the compound in question. To standardize the annual amount of rainfall, additional irrigation is carried out so that a total of 800 mm water (precipitation and irrigation) is applied to each lysimeter per year. During the studies, important climatic parameters are recorded: Air temperature and soil temperature in a depth of 10, 30 and 80 cm is measured with "Thermo 2" (Eijkelkamp), precipitation is measured with an automatic rain collector (Eijkelkamp) and soil moisture is measured in a depth of 10, 30 and 80 cm using "Tensior 6" (U+P). All data are recorded using a multi-channel logger (Delta-T Devices).

SAMPLING PROCEDURE

Soil samples are taken in autumn and spring of every experimental year. After pesticide application to the soil, three randomized samples are taken from each lysimeter from a depth of up to 30 cm and devided into 10 cm segments. After pesticide application to plants radioactivity in soil is not distributed homogenously. Therefore the 0 - 10 cm soil layer of the whole lysimeter is removed in the time between harvest and seeding of the following crop. The soil is mixed, simulating soil tillage, weighed and a sample is taken for analysis. After taking the randomized samples from the 10 - 20 and 20 - 30 cm soil layers and refilling the holes with non radioactive soil of the same kind, the mixed surface soil layer is replaced. At the end of the study, the 0 - 10 cm layer is removed again, weighed and a sample is taken after mixing. In addition, soil samples of the whole soil profile are taken and fractionated every 10 cm to obtain a total balance sheet of the remaining radioactivity at the end of the experiment. Plant samples are taken at harvest time and the plant material, which would remain on the field in agricultural practice is returned to the lysimeter after the analysation of aliquots. Percolate is collected once a month during summer time and twice a month from October to April because large quantities of percolate can be expected in this part of the year without vegetation.

THE LYSIMETER FACILITY AT THE CROP PROTECTION RESEARCH CENTER, BAYER AG, MONHEIM, GERMANY

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ABSTRACT

A recently installed lysimeter facility is used to study the long-term behaviour of ^{14}C-labelled pesticides under realistic field conditions. In contrast to other lysimeter facilities the system described here in consists of lysimeters with undisturbed soil monolithes up to 2,0 m and a technical control corridor below ground. The bottom of the individual lysimeter is accessible through insulated windows even after installation.

INTRODUCTION

Pesticides get onto the soil either directly or indirectly via plants, and their initial concentrations in the soil may be very low. This will depend upon the rate of application and the degree of coverage of the soil with vegetation. Whether a pesticide and/or its metabolites are translocated into deeper soil layers depends upon a great number of complex, interacting factors

After application of a pesticide the initial concentration may be considerably reduced by a series of substance-specific properties and climatic influences. Such factors are photolysis and hydrolysis on leaf and soil surfaces, volatilization from plants and soil as well as erosion by wind and water (run-off). In the soil itself translocation is determined by adsorption and desorption, biotic and abiotic factors incorporation into the soil matrix, soil properties, vegetation, application rate and water movement in the soil.

The translocation behaviour of a pesticide in the field can be assessed by residue methods. However, particular difficulties arise with the "complete" collection of the leachate as well as with the determination of the proportion of "bound residues". Therefore, the lysimeter concept was developed which allows the use of radioactively labelled active ingredients under field conditions.

Lysimeter experiments have been required since 1990 as an integral part of the risk assessment of pesticides in the German registration procedure (Anonymous 1990).With the positive identification of a pesticide or its metabolites in the leachate of the lysimeter, a groundwater monitoring study at a field site of potential application is proposed (including this book, Hellpointner et al.).

CONSTRUCTION OF THE LYSIMETER STATION

The construction and operation of lysimeters has been described in several publications (including this book). At Bayer experience with undisturbed soil cores in lysimeters (Jarczyk, 1983) goes back to 1975.

In connection with the construction of a lysimeter facility the question arises whether the lysimeter should be freestanding or lowered into the ground. It is much cheaper to install freestanding lysimeters than those sunk into the ground. However, the temperature of above ground lysimeters tends to follow ambient temperature which deviates from the field situation. In winter the temperatures in lower soil layers of the lysimeter are too low and in summer they are too high. Furthermore, the lack of a crop surrounding in the lysimeter is a distinct disadvantage. Consequently, the conditions of wind and rainfall on the exposed lysimeter surface do not correspond with those of the field situation. An increased evaporation from the test plot is to be expected. In order to simulate practical conditions as closely as possible, it is therefore recommended to work with lysimeters which are lowered into the ground rather than with freestanding lysimeters.

The following factors determine the size of a lysimeter facility:

- Number of active ingredients to be investigated per year (including the variables formulation, rate of application, crop).

- Projected test duration (acclimatization phase, test period).

- Number of replicates.

- Number of soils.

- Basic scientific aspects (e.g. depths of the lysimeter and leaching behaviour in unsaturated and saturates conditions).

The lysimeter facility of Bayer AG in Monheim was designed for 28 lysimeters. It consists of 2 water-tight concrete containers (about 6 m x 22 m) with 14 lysimeters arranged in two rows of 7 (Figures 1 and 2). The rectangular lysimeters have a surface area of 1 m^2 and a depth of 1.3 m (Fig. 3). It is also possible to install 8 lysimeters with a depth of up to 2 m in the unit.

The lysimeters are lowered in the container to ground level and each lysimeter is placed in the centre of a field plot of 8 m^2. The lysimeter stands in a steel container which holds back the soil of the surrounding field plot and thus allows moving the block into and out of the unit. The steel containers are screwed to the surrounding concrete container. The complete steel construction has been produced by Wolf Incor., 5190, Stolberg. FRG. The gap between steel container and lysimeter is covered by a plastic frame about 1 cm high, which surrounds the area of exactly 1 m^2 and ensures that the correct amount of water gets onto the lysimeter during rainfall.

The concrete container surrounding the lysimeter is filled with:

- Gravel (∅ 8-12 mm) in the bottom layer (about 30 cm).
- Sand in the middle layer (up to 70 cm below ground level).
- Loamy sand on the top layer.

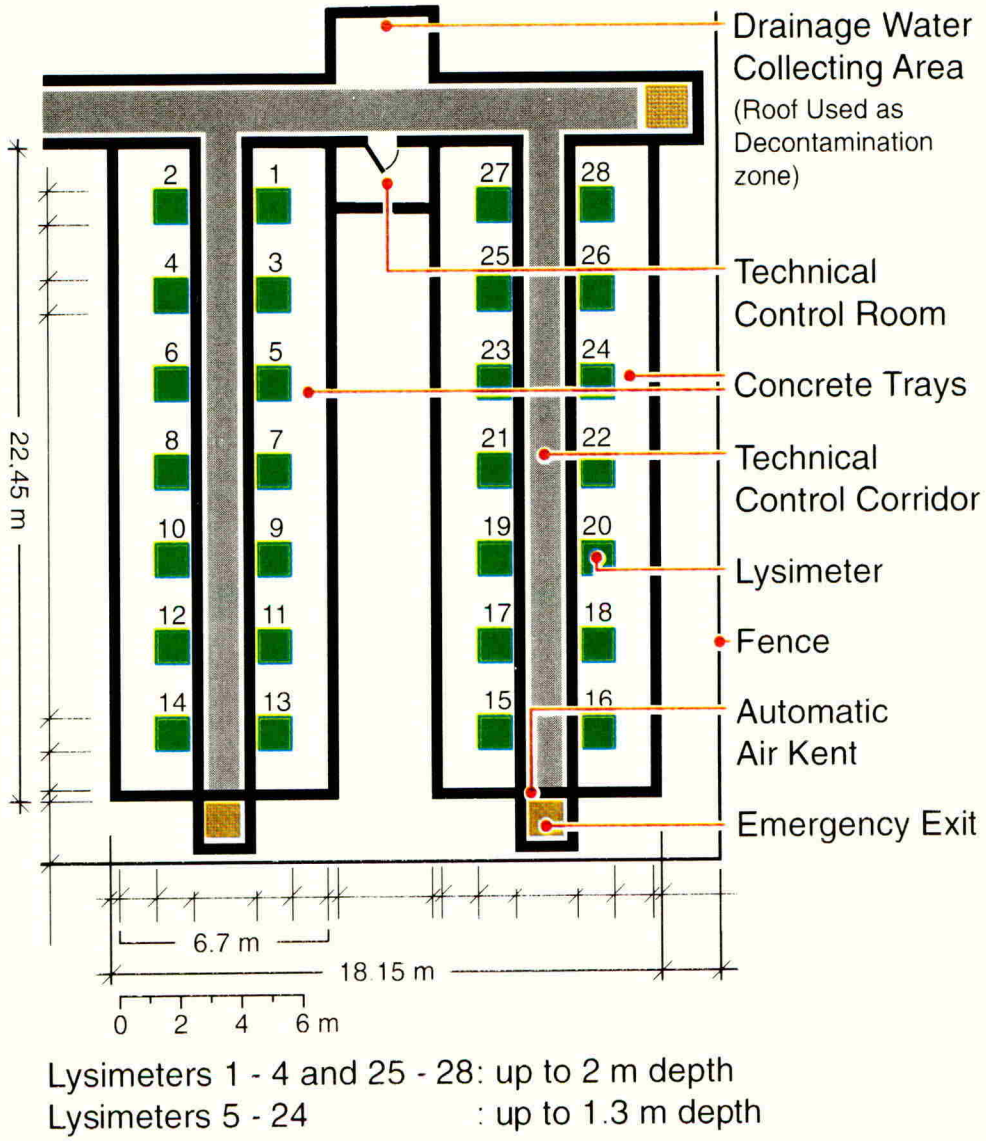

Figure 1: Lysimeter Facility, Bayer AG, Monheim
Below Ground Level

Drainage pipes ensure that the excess water flows out of the concrete container. The water is collected and pumped into a waste water tank. Radioactivity measurements in the drainage water can be carried out immediately.

The lysimeter unit is reached via a control corridor between the lysimeters. The field soil above this underground corridor is about 70 cm deep.

Investigation of the Degradation of Pesticides and of the Translocation

- to Deeper Soil Layers
- into the Leachate

under Field Conditions

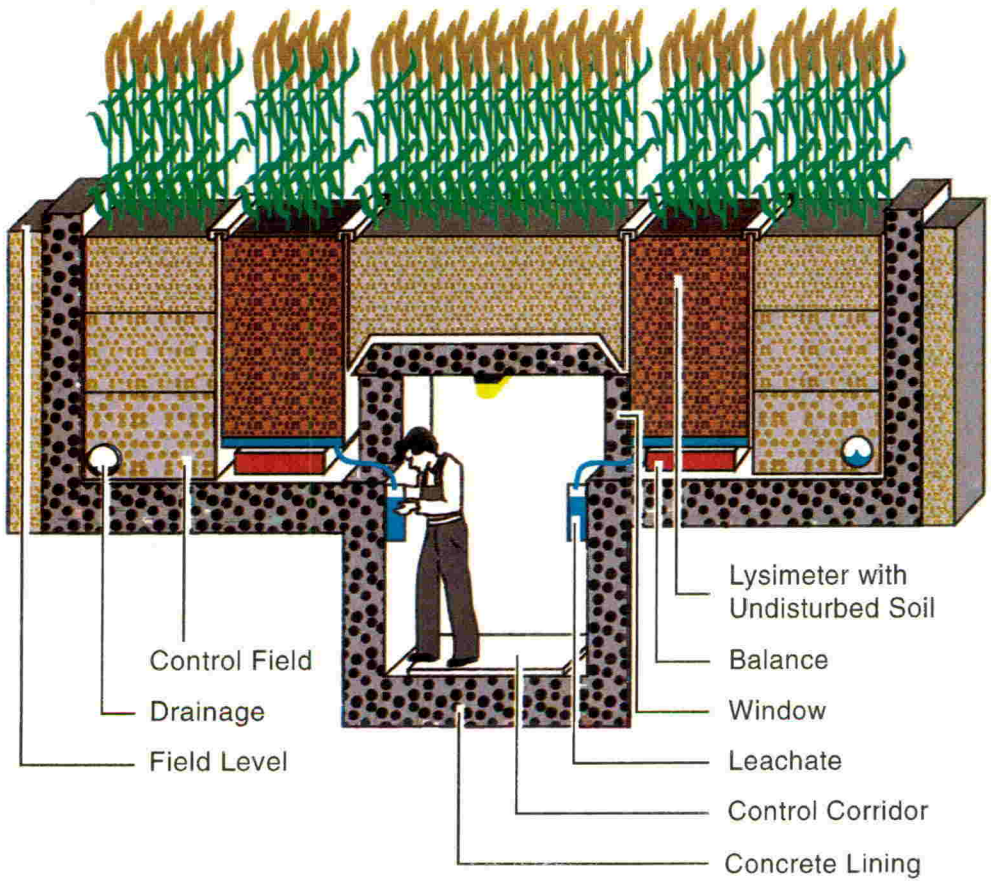

Figure 2: Lysimeter Facility, Bayer AG, Monheim
Cross Section

The individual lysimeters are accessible through insulated windows so that after installation, sensors can be installed or a ground water level can be simulated at a depth of 1.3 m or 2 m.

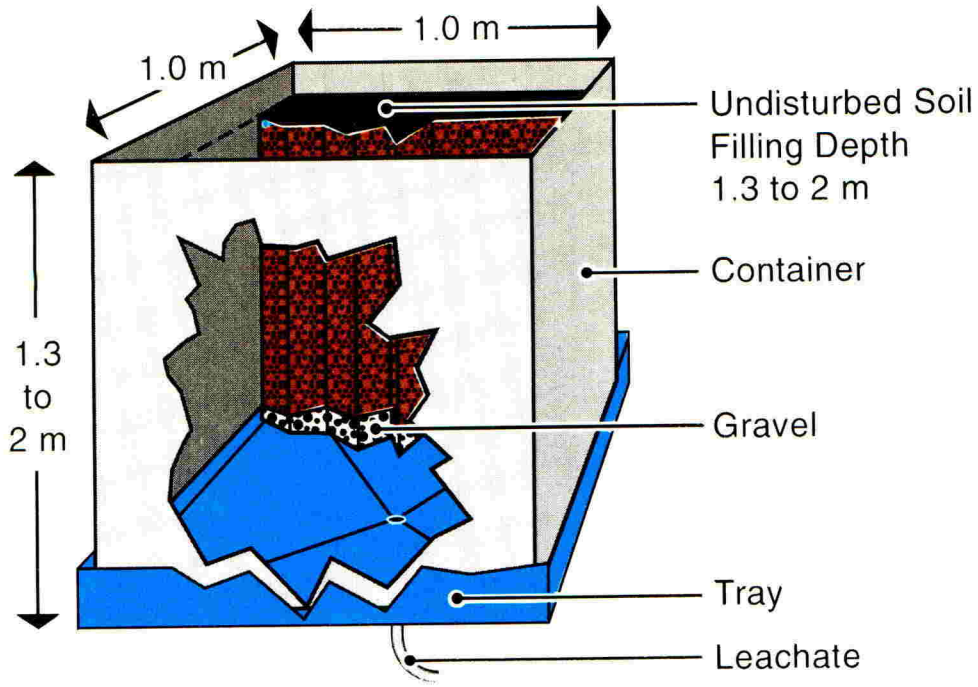

Figure 3: Lysimeter Design

The leachate is collected in steel containers placed on shelves along the wall of the underground corridor. Ten lysimeters are placed on balances. Weight changes of >500 g are determined via four ring weighing cells each. Thus, the water regime of the lysimeters is continuously recorded over several years.

Although the two underground corridors are not air-conditioned, the temperatures in the corridors and in the soil at a depth of 1.3 m have so far been in good agreement. Ten minutes before entering the underground corridors, and during work in the facility, the corridors are provided with fresh air. The temperature of the introduced fresh air corresponds to that of the surrounding soil at a depth of 1.3 m. At present the air is exchanged 5 times per hour. First results concerning the temperature profile in a lysimeter in comparison to measurements in a neighbouring weather station are available and confirm a good agreement between the temperatures in the lysimeters and in the field.

Soil selection and characteristicis

In principle, nearly every agricultural soil could be used to study the long-term leaching behaviour of pesticides using the lysimeter approach. Due to the high variability in physical and chemical parameters of soils and the limited lysimeter

Name

German Soil Classification (1982): Braunerde

FAO: Eutric Cambisol

Ah	0- 30 cm
Bv	30- 60 cm
Bv	60-100 cm
Bv	100-115 cm
II Bv	115 - 135 cm
III Bv	135-155 cm
IV Bv	155 - 200 cm

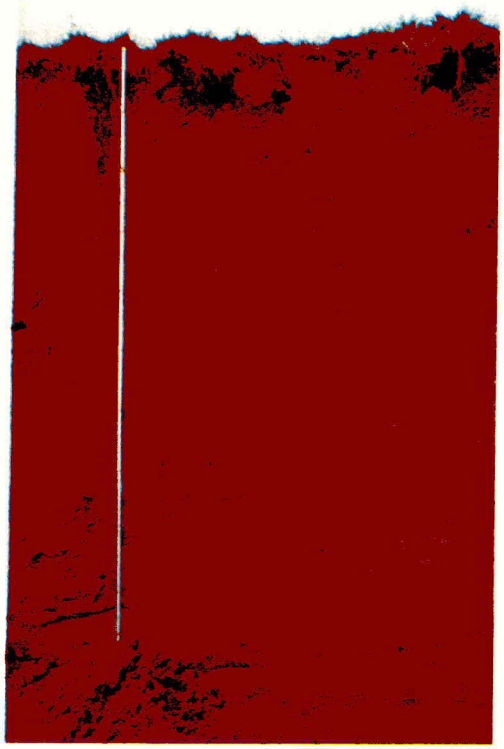

Figure 4: Soil Profile of the Experimental Farm Monheim, Bayer AG

capacity, the federal registration agency in Germany follows the "worst case" concept for the selection of soils rather than the typical agricultural soil used for specific crops. The main selection criteria are the soil texture (minimum 70% sand, maximum 10% clay) and the soil organic carbon content (maximum 1.5%).

Some of the chemical and physical properties of the soil used at the Bayer lysimeter facility are presented in Table 1.

Table 1: Chemical and physical properties of the sandy loam (Eutric Cambisol) lysimeter soil, origin experimental farm Monheim, Bayer AG

Depth cm	pH H_2O	pH $CaCl_2$	C_{org}[1] weight %	CEC[2] meq/ 100 g	Soil texture USDA	Microbial Bio-mass[3] mg/kg
0 - 30	7.04	6.05	1.41	9.61	sandy loam	235
30 - 60	7.24	6.42	0.34	7.43	sandy loam	34
60-100	7.18	6.32	0.19	7.57	loamy sand	11
100-115	7.46	6.61	0.17	8.52	loamy sand	13
115-135	7.41	6.63	0.09	4.73	sand	-
135-155	7.37	6.74	0.15	11.07	sandy loam	-
155-200	7.64	6.41	0.07	5.46	sand	-

1 C_{org} Organic carbon
2 CEC Cation exchange capacity
3 According to Anderson Domsch (1979)

All data obtained by the Department of Soil Science, University Gießen, Dr. Gäth.

In addition to the above mentioned parameters it is extremely useful to get indications about the water regime within the undisturbed soil. The parameters in Table 2 are essential to simulate the water regime and the movement of a pesticide in the soil core.

Table 2: Physical parameters of a sandy loam (Eutric cambisol)

Depths	Pore volume	AC pF<1.8	FC pF 1.8	AWC 1.8-4.2.	PWP pF 4.2	K	k
cm	Vol. %	Vol. % H_2O				cm x s^{-1}	cm^2
0 - 30	44.94	12.49	32.45	23.83	8.83	5.39×10^{-3}	5.39×10^{-8}
30 - 60	37.97	17.36	20.61	13.10	7.51	9.76×10^{-3}	9.76×10^{-8}
60 - 100	42.47	24.31	18.16	10.46	7.70	7.50×10^{-3}	7.50×10^{-8}
100 -115	42.90	21.64	21.15	11.82	9.43	5.53×10^{-3}	5.53×10^{-8}
115 -135	45.49	35.74	9.75	7.34	2.41	2.91×10^{-3}	2.91×10^{-8}
135 -155	38.27	3.52	34.75	22.74	12.01	2.87×10^{-4}	2.87×10^{-9}
155 -200	42.26	26.47	15.79	9.74	6.04	1.87×10^{-3}	1.87×10^{-8}

AC - air capacity = pore volume - FC
FC - field capacity
AWC - available water capaciity = FC - PWP
PWP - permanent wilting point
K - saturated hydraulic conductivity
k - intrinsic permeability $k = K \times 10^{-5}$

All data obtained by the department of soil science, University Gießen, Dr. Gäth.

Due to the high proportion of sand and of coarse pores the saturated hydraulic conductivity (K), i.e. permeability (k) is classified as high. As a consequence the air capacity (AC) is also high. With the exception of the A_h horizon the field capacity (FC) is low and this also follows for the available water capacity (AWC).

Acquisition of the lysimeters

The lysimeters are obtained by pressing a square steel frame with edges of 1 m each and a height of 1.34 m or 2.04 m into the ground by means of the grab of a digger. Between the steel frame and the grab there is a steel plate, about 4cm thick, which rests on the steel walls. The lower end of the 1 cm thick steel frame tapers off in the centre. Only stainless steel is used for the lysimeters. To ensure straight penetration of the steel frame into the ground the native soil surrounding the lysimeter is not normally removed. Only when considerable difficulties are encountered in the processes of pressing and excavating carried out alternately. Penetrating is complete when only about 5 cm of the steel frame remains above the soil surface. The compaction of the soil in the lysimeter during acquisition is very low and amounts to about 2 cm at the edges. After lowering the steel frame, the surrounding soil is removed and a cutting device is placed at the lower end of the lysimeter frame so that the cutting plate just fits underneath the lysimeter. The cutting plate is then pulled under the lysimeter and the soil monolith is separated from the ground below.

The lysimeter, including the cutting plate, is placed into a 10 cm high stainless steel tray which is half filled with gravel (particle size 8 to 12 mm). The cutting plate is pulled out and the soil block, now standing on the gravel bed, is adjusted. The gravel bed ensures good continuity with the lower part of the lysimeter which is not usually completely uniform and it prevents water from accumulating in the soil. The outlet for the leachate is located at the bottom of the tray (Fig. 3). Stainless steel mountings are fixed on opposite sides of the tray so that the lysimeter can be lifted and placed into the steel container.

Examination of the lysimeter blocks

After acquisition of the lysimeters the question arises whether the block has been removed without disturbing the soil structure and without the development of cracks. Were stones moved in the soil during acquisition leaving cavities? Does the soil adhere optimally to the steel walls? Furthermore, there should be no vole and/or mole burrows present in the soil.

At present there is no procedure to answer these questions immediately after acquisition. Only at the end of the lysimeter experiment when the block is removed, in layers of 10 cm , possible irregularities in the soil structure such as burrows, holes and/or cavities can be found. On the basis of the amount of leachate and with the aid of tracers it is possible at best to estimate whether a block meets the requirements for a test. It is possible, for instance, to draw up percolation curves of the lysimeter blocks by using tritiated water and comparing these curves with each other may give an indication of the usefulness of the lysimeter blocks. The use of tritiated water offers the advantage that tritium can be measured in the counter simultaneously with ^{14}C.

Experiments were carried out on 1 m^2 blocks using 28 MBq tritiated water in 40 ml water (May 16, 1991). Traces of tritium were found in the first leachates 6 and 18 days after application (24 to 90 Bq/l). About 1 year after application the amount of tritium in the leachate reached a maximum of 15-24 KBq/l. If high amounts of tritium

are determined in the leachate immediately after tritium application and/or if great differences are noted between two lysimeters, it is necessary to carry out further preliminary experiments or to discard the lysimeter with the extremely high tritium concentration in the leachate.

Application

The application of the active ingredient to the lysimeter should be made as close to practice and as uniformly as possible. It is recommended to use flat fan nozzles which are moved over the lysimeter. From experience, losses of material which neither reach the crop nor the soil amount to about 10%. This comprises active ingredient remaining in the sprayer and the tank as well as spray deposit on the protective walls used to prevent cross contamination. When preparing the application solution, the addition of an amount corresponding to these losses should be taken into consideration.

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Jarczyk, H. J. (1983) Lysimeter Installation of Bayer Agrochemicals Division at Leverkusen. Pflanzenschutz Nachrichten, Bayer, 36, 1-20

THE LETCOMBE LYSIMETER STATION.

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ABSTRACT

The collection and installation of soil monoliths in the Letcombe lysimeter is described in this paper. The monoliths are collected in large glassfibre cylinders (0.5 m^2 area x 1 m deep) using a piling technique, are sealed into metal base plates with drainage holes for the removal of leachate and are transported to and installed into the lysimeter complex at Letcombe. Three agricultural soil types are held at present (sand, medium loam over clay and uniform loam) and passive tracer experiments have shown that sidewall flow effects are minimal. Methods of cultivation, irrigation, maintainance of a guard crop and application of test compound are also discussed.

INTRODUCTION

Lysimeters are soil monoliths that can either be made by filling suitable containers with soil and allowing them to settle or more realistically, are undisturbed soil monoliths that are collected intact. The size, method of drainage, installation (buried in the ground or standing above ground) and use of crop cover vary considerably among lysimeters used by various research groups. Bergstrom (1990) has written a comprehensive review of lysimetry considering aspects such as size, shape, method of filling, soil type selection, types of drainage system, use of cover crop and additional field measurements which are all important considerations when conducting such studies.

The lysimeter complex at the DowElanco Research and Development centre at Letcombe was built by the Agricultural Research Council during the 1950s and, over the years has been used to study radionuclides on pasture, the movement of water in soils, the behaviour of fertilisers in soils and for plant physiology experiments (e.g. the behaviour of plant root systems in water-logged soils). The site was purchased by DowElanco in 1986 and the lysimeter was refurbished in 1989. The complex consists of an underground compartment with bays to accommodate up to 60 lysimeters. The tops of the lysimeters are open to the air and, therefore, are exposed to normal climatic conditions. Because of the design, access is available to the sides (for inserting measuring probes) and bases (for collection of leaching water or the creation of artificial water tables) of the lysimeters .

The facility is used to study the fate and behaviour of both new and existing products under conditions as close to practical agriculture as possible. Protocols are written to cover as many proposed practical uses as are reasonably possible (e.g. different

soil types, autumn and spring applications, several target crops, multiple applications during a single season and repeated applications in successive seasons) in order to gain a realistic appraisal of the potential environmental impact of the use of the pesticide. The first experiments were started in 1989 and studies are conducted for a minimum of 2 years.

The comments and observations below are from the experiences gained during the first 3 years at the Letcombe Lysimeter.

DESCRIPTION OF SYSTEMS

Soil Selection

In principle any soil type could be studied in lysimeters but obviously, heavy clays, chalky soils and flinty/stoney soils will be difficult to collect. At Letcombe three soil types have been selected for routine use (Table 1). These are a sandy soil (Cuckney series, in compliance with the German BBA guideline on lysimeter studies, Fuhr **et al.**, 1990), a medium loam over clay (mloc, Oxpasture series) and a loamy soil (Sutton series, uniform to a depth of ca. 80 cm). The latter 2 soils were chosen as being representative of heavier, less freely drained agricultural soils of a type common in the UK and are of particular importance to aquifer contamination where they overly porous subsoils such as sandstones, limestones or fractured chalk, all of which may contain aquifers. Sandy soils of the type used are found in midland and south eastern England, Belgium, Holland, Luxembourg, France, Spain, Denmark and West Germany (Hollis, 1989a). Water movement through the sandy soils will be predominantly by pore-flow and these soils will all have an associated perched water table or aquifer. Soils of the loamy and mloc type can be found extensively in midland, eastern and southern England and similar soils can be found in Belgium, Luxembourg and West Germany (Hollis, 1989a, Beard, 1991). Water movement through the lower parts of the mloc soils in the lysimeters is predominantly by by-pass flow through earthworm holes (estimated as 0.02% of the area of the lysimeter at 83-110 cm depth, Hollis, 1989b).

Saturated hydraulic conductivity values (Ksat) were determined as 7.8-35.7 cm. h^{-1} for the sandy soils, 1.8-6.3 cm. h^{-1} for the mloc soils and 22.3-23.7 cm. h^{-1} for the loamy soils which were of the correct order for the soil types (Hollis and Woods, 1989) and experiments with Cl^- and Br^- as passive tracers (Saffigna **et al.**, 1977) showed that there were no significant side wall effects with these lysimeters.

Collection and Installation of Lysimeters

The lysimeters were collected using a system based on that developed by the ARC (Belford, 1979; Leake, 1991; Fig. 1) and the operation was carried out by the Soil Survey and Land Research Centre, Silsoe College, Silsoe, Bedfordshire, England. Fibre glass cylinders (0.80 m diam. x 1.1 m depth, wall thickness 7-8 mm) were seated in mild steel cutting rings and a reinforced steel plate placed on top. The back hoe of a mechanical digger was used to push the whole assembly into the ground in approximately 15 cm steps and

the surrounding soil was dug away at each step. When the cylinder had been pushed into the ground to a depth of 1 m, a steel frame was connected to the bottom of the frame and a cutting plate was pushed

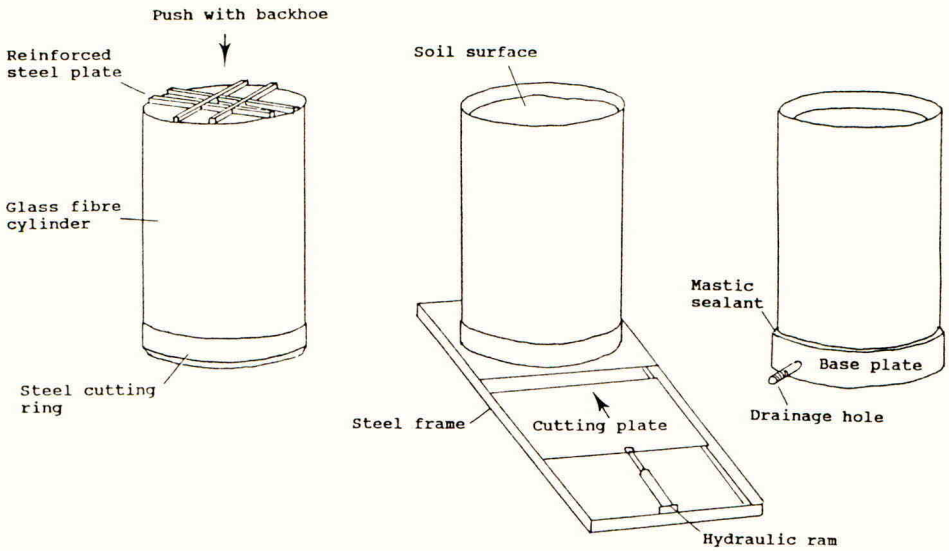

Figure 1. Stages in the collection of undisturbed soil monolith Lysimeters.

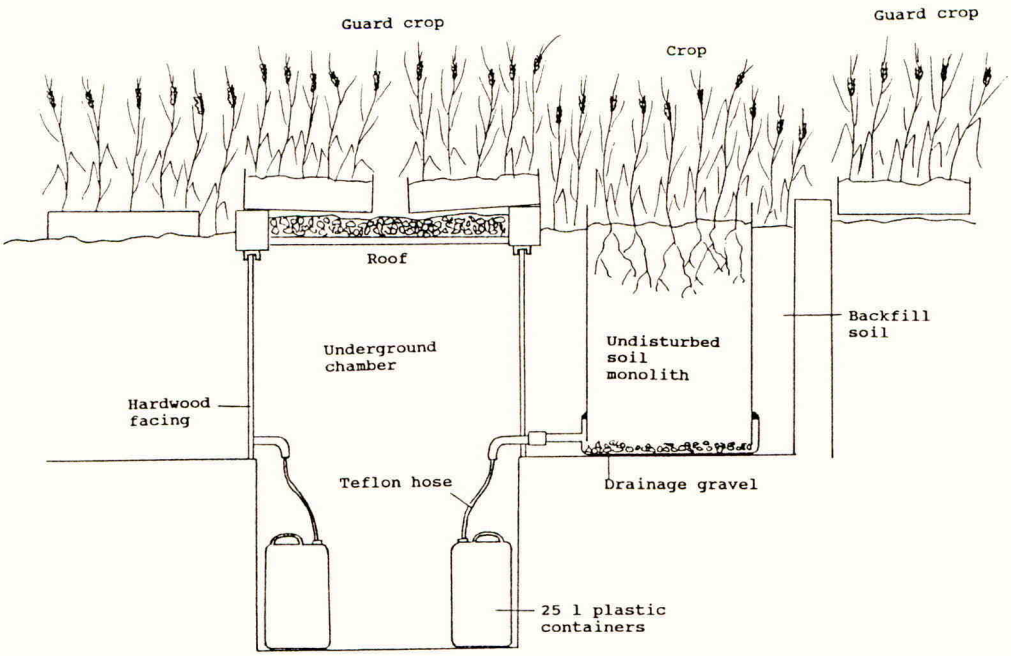

Figure 2. Cross section of the Letcombe Lysimeter installation.

TABLE 1. Analytical data for the 3 soils used in the Letcombe lysimeter.

Horizon[a], Depth (cm)	% sand[b]	% silt[c]	% clay[d]	% OC	pH[e]
Sandy soil					
Ap,(0-29)	88	6	6	0.6	6.2
Bw,(29-50)	88	7	5	0.2	6.2
Bw,(50-73)	90	5	5	0.1	5.4
Cu,(73-100)	86	2	12	0.1	6.0
Medium loam over clay					
Ap,(0-27)	55	27	18	0.9	7.0
Eb(g),(27-40)	57	28	15	0.5	7.0
Bt(g),(40-69)	54	26	20	0.5	7.0
2BCt(g),(69-83)	85	4	11	0.1	7.1
3BCt(g),(83-100)	26	25	49	0.2	7.1
Loamy soil					
Ap,(0-22)	52	29	19	2.49	6.5
Bt(g),(22-52)	49	25	26	0.83	7.6
2BC,(52-79)	67	15	18	0.55	8.0
2BC2,(79-92)	77	16	7	0.19	8.4
3Cu,(92-100)	90	7	3	0.11	8.5

[a] [e] Hodgson, 1976, [b] sand=60-600 μm, [c] silt=2-60 μm, [d] clay=<2 μm, 1:2.5 in water.

under the monolith using a hydraulic ram. A new top plate (for lifting) was attached and, with the cutting plate acting as a base plate, the undisturbed soil monolith was lifted from the hole. The monolith was then inverted, the frames were removed and course gravel (ca. 2-3 cm) was placed on the bottom to aid drainage. Mild steel base plates, each with a drainage tube, were placed over the bottoms of the monoliths which were then returned to the upright position. The gap between the glass fibre cylinder and the base plate was sealed with a special mastic and the lysimeters were transported back to Letcombe for installation in the lysimeter complex in bays which are then filled with soil to allow guard crops to be grown around the lysimeters (Fig. 2). Leachate collection vessels (25 l) were connected to the drain tubes of each lysimeter. This method of collection worked extremely well and allowed 2-3 lysimeters to be excavated per day depending on the soil type and the weather conditions.

Maintainance of Lysimeters

The lysimeters are cultivated, fertilised and sown with suitable crops in accordance with normal agricultural practice. Proprietary seeds and fertilisers are used at recommended rates. The presence of a crop is an important consideration as it creates realistic upward movement of water in the form of evapotranspiration which is of particular importance in spring. Appropriate crop rotations are mimicked for the test compound. To date cereals, oilseed rape, field beans, sugar beet and pasture grass have all been successfully cultivated. Pest control agents are also used in accordance with agricultural practice to control infestations of weeds, fungi or

insects within the lysimeter complex.

Guard crops are grown in the soil surrounding the lysimeters but because of the small size of the guard area, addition guard crops are grown in trays placed adjacent to the lysimeters in order to increase the guard crop area (Fig. 2). The guard crop is particularly important for the maintainance of realistic soil surface temperatures and a large guard crop will also minimise crop edge effects.

Application of Test Chemical

To date only radiolabelled test chemicals have been used in lysimeter experiments at Letcombe as this maximises the information that can be gained from these experiments (Fuhr, 1977). This provides a complete picture of the distribution of the test chemical and any metabolites between the crop, the various soil layers and soil solution although a complete balance is not possible because no attempt is made to trap volatile components. Test chemicals are formulated and dispersed as spray solutions in water. Applications should be made at realistic rates but with chemicals used at low rates this is not always possible if the specific activity of the test chemicals is too low, in which case higher rates must be used to ensure accurate and meaningful data. Three methods of application have been assessed in an attempt to make the treatment as realistic as possible. 1) Hand operated garden sprayers (spray vol = 23 cm^3). These gave even coverage but had extremely variable droplet sizes, 2) Stationary FL-8VS fulljet solid cone nozzles mounted above the lysimeter (operating pressure 300 kPa, spray vol = 30 cm^3). These gave very high concentrations of spray immediately below the nozzle and high concentrations at the outside of the spray pattern, 3) Teejet 8005-E nozzle mounted in a dolly moving above the surface of the lysimeter (operating pressure = 300 kPa, spray vol = 30 cm^3). These gave a reasonably even spray distribution but because they spray a rectangular profile, they were very wasteful of test chemical. None of the above techniques is ideal but all are attempts to make a realistic application. All three methods have been used in different experiments over the last 3 years.

Collection of Leachate and Soil Samples

The lysimeters drain by gravity into 25 l containers which are emptied at least once a week (when there is leachate). The stability of the test chemical and metabolites under these storage conditions must be assessed. The volume and pH of the leachates are recorded at each collection. Over the course of a 2 year experiment as much as 300-400 l of water may be collected from each lysimeter and most of this will have to be disposed of as low level radioactive waste.

Soil cores are taken after each harvest (1 core, 5 cm diam. x 50 cm deep) and at the end of the experiment (6 cores, 5 cm diam. x 100 cm deep) using a Humax electrically driven soil corer. The holes are back filled with untreated topsoil of the appropriate type for the lysimeter being sampled, this is tamped down to ensure good packing and then the positions of the holes are marked.

Irrigation

The Letcombe lysimeter complex is outdoor so the lysimeters receive natural precipitation. At Letcombe the average annual rainfall for 1941-70 was 705 mm and for 1975-83 was 700 mm with the bulk of this falling during the winter months. Because the German guideline on lysimeter studies stipulates 750-850 mm of rain it is necessary to irrigate during the summer months. This is done by comparing rainfall for the first and second halves of each month with half of the monthly average for Hamburg and then making up the deficit by watering during the subsequent half month. The water is added using a watering can and, whenever possible, is done early in the morning or during a rain event.

Chemical Analysis

Because radiolabelled test chemicals are used, all chemical analysis is by radiochemical techiques such as liquid scintillation counting, combustion, thin layer chromatography (tlc) and radio-tlc scanning.

DISCUSSION

Experiences gained since 1989 have highlighted several important practical considerations. The application of the test chemical is, obviously, critical because too large droplet size could lead to excessive run-off from the plant leaves onto the soil or, uneven spray distribution could result in an enhancement of edge effects. Realistic application is no simple matter because a tractor sprayer moving at 8 km/h covers 1 m in less than 1 s and in order to reproduce this, each lysimeter has to be sprayed with 10-20 cm^3 of spray solution in less than 1 s. The size of the guard crop is also important as too small or thin a guard crop can lead to higher soil surface temperatures than would be measured in the field. This in turn could lead to enhanced degradation rates of the test chemical. The guard crop also minimises crop edge effects within the treated lysimeters. The irrigation of lysimeters has also caused some problems. Watering was sometimes carried out when air temperatures were >20°C and the relative humidity was low, i.e. conditions when it would not naturally rain. In general, watering under these conditions leads to significantly earlier onset of leaching from the irrigated lysimeters compared to non-irrigated lysimeters. It could lead to plant scorching which would leave the plants in a weakened condition making them more prone to fungal infection. The warm moist condition of the soils could also lead to enhanced microbial degradation rates.

One final point of consideration is the taking of soil cores during the experiment. Whilst these provide valuable information on the movement of the test chemical down the soil profile, they also severely disrupt the structure of the soil monolith and could provide routes for preferential water movement. For this reason soil cores taken during the experiment are taken to 50 cm so as to leave the bottom half of the soil profile intact. In future, extra lysimeters will be treated for the sole purpose of providing soil cores. The use of narrow diameter lysimeters (ca. 10 cm dia.) for more frequent

sampling in parallel with the large lysimeters has been tried but it is not possible to grow crops in these so the water movement is not the same as in the large lysimeters. Additionally, wall effects are probably more pronounced in these smaller lysimeters (Bergstrom, 1990) and for these reasons it was felt that their use was not appropriate.

Although lysimeter experiments give a lot of extremely valuable data they are very expensive and have hidden running costs which need to be considered. These include the cost of collection of the soil cores, the cost of disposal of large quantities of low level contaminated leaching water and, at the end of the studies, the disposal of several tonnes of radioactive soil. These can be a considerable part of the overall cost of lysimeter studies.

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A SWEDISH LYSIMETER TEST SYSTEM SUITABLE FOR STUDYING FATE AND BEHAVIOUR OF PESTICIDES IN SOILS

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ABSTRACT

A lysimeter system suitable for studying dissipation of pesticides in soils is described. The lysimeters consist of plastic pipes (PVC) encasing soil monoliths that are ca. 1 m high and 0.3 m in diameter. After collection, the lysimeters are placed in a lysimeter field measuring station at Uppsala, Sweden. In a standard leaching test, two soil types (one sand and one clay soil), two irrigation treatments and the normal application rate of the studied pesticide are used. Both the soil types and the irrigation treatments are replicated, usually in triplicate. A tracer (^{36}Cl) is also applied on the lysimeters to follow the pattern of water movement through the profiles. All management practices are performed to mimic actual field conditions as closely as possible. Collection of the monoliths, installation of the lysimeters in the measuring station, and various management and sampling procedures are discussed in the paper. The presentation is focused on the use of these lysimeters for studying pesticide mobility.

INTRODUCTION

An increasing awareness of environmental quality has modified our views concerning the evaluation and use of various agrochemicals. We now realize the importance of not only considering the effectiveness of pesticides, but also their persistence and mobility in soils. Accordingly, many approaches to studying dissipation and mobility have been employed, ranging in scale from watershed studies (Norris et. al., 1984) down to lysimeters or soil columns (Leistra et. al., 1976; Führ, 1985; Bowman, 1988; Bergström, 1990a).

In studies of pesticide movement in soil, it is extremely important to maintain control over all water percolating through the soil profile. Moreover, control over environmental factors is also crucial since the bioactivity of many pesticides is strongly coupled to pH, soil temperature, texture, and so on (e.g. Anderson, 1985). With respect to both these conditions, lysimeters offer good possibilities for conducting relevant experiments. Therefore, lysimeters have been used extensively during the last few decades for a great variety of pesticide dissipation studies (see review by Bergström, 1990b). Differences between experimental systems usually concern lysimeter size, soil filling technique and

methods for measuring pesticide fluxes.

In the following presentation, a Swedish lysimeter test system is described with regard to selection and collection of soils, installation of lysimeters in a measuring station, and various management and sampling procedures performed.

SOIL SELECTION AND COLLECTION OF LYSIMETER MONOLITHS

Soil type is one of the major factors influencing dissipation of pesticides (Anderson & Humburg, 1987). Soil texture affects the water-holding capacity of a soil and thus the pesticide leaching load, since it is closely associated with the amount of water passing through the soil (Leistra, 1980). There is also evidence that preferential flow in soils with normally low hydraulic conductivity, such as clay soils, can cause considerable leaching of pesticides (Bergström & Jarvis, 1992). This means that it cannot be safely assumed that measurements of leaching loads in sandy soils necessarily represent "worst-case" conditions. Soil texture may also have indirect effects on pesticide leaching. For example, a high soil-water content in a clay soil may result in formation of anaerobic microsites, often reducing pesticide breakdown considerably (Anderson & Barrett, 1985). The period during which the compound is exposed to leaching is thereby extended. Furthermore, many pesticides are affected by the organic matter content and the pH of a soil, which influence leachability considerably (e.g. McGlamery & Slife, 1966; Fredrickson & Shea, 1986).

From the above it can be concluded that in a standardized lysimeter test system for pesticides, several different soil types should preferably be included, at least one of which is a structured soil. In the Swedish test system two "benchmark" soils have been identified as being suitable for dissipation studies of pesticides, i.e. a sandy soil (Mellby) and a clay soil (Lanna). The chemical and physical properties of these two soils are shown in Table 1.

The filling of lysimeter containers with soil has to be given considerable attention because of the need to create conditions representative of actual field situations. Filling containers with repacked disturbed soil is certainly easier than collecting undisturbed soil monoliths. Clear differences, however, in the movement of water and solutes occur between soils collected with the two techniques (Cassell *et al.*, 1974; Bergström, 1987), which are especially pronounced for well-aggregated and stratified soils. Therefore, undisturbed soil is a requirement when studying pesticide mobility. A number of different techniques for collecting undisturbed soil have been developed (e.g. Belford, 1979; Brown *et al.*, 1985).

In the sampling method used in Sweden undisturbed soil monoliths are taken in plastic (PVC) standard sewage pipes (0.295 m inner diameter and 1.18 m length) using only a small or zero hydraulic pressure to push the pipe down into the soil (Persson & Bergström, 1991). The method is based on a drill, consisting of

TABLE 1. Soil characteristics of the Mellby and Lanna soils.

Soil	Soil texture	O.M. (%)	CEC ($cmol_c kg^{-1}$)	Bulk dens. ($g\ cm^{-3}$)	$\theta_{1.0}$ (%)	pH
Mellby						
Topsoil	S. loam	5.9	14.3	1.45	30	6.2
Subsoil	Sand	0.4	3.9	1.64	14	5.7
Lanna						
Topsoil	Clay	3.8	28.4	1.21	46	7.2
Subsoil	Clay	0.0	33.6	1.42	43	7.4

The soil texture classification is according to the USDA soil classification system.
$\theta_{1.0}$ = Volumetric water content at a tension of 1 m water (estimated field capacity).

a steel cylinder with four mounted cutting-teeth at the bottom, into which the plastic pipe is inserted (Fig. 1). The steel cylinder rotates around the pipe and carves out a soil core which is gently pushed into the pipe. The main advantage with this technique is that the soil is less disturbed compared with methods in which the lysimeter casing is pressed down into the soil with greater pressure.

Different soil types have varying degrees of suitability for lysimeter studies related, to a great extent, to collection techniques. Heavy clay and peat soils usually shrink upon drying, which may cause unacceptable water flows along the casing wall. To minimize this problem in our studies, structured soils are collected when they are as dry as possible (just after the growing season in the autumn). Upon rewetting all cracks and gaps between the soil column and the lysimeter wall then disappear as a result of swelling. When put in lysimeters, heavy clay soils may have another problem that is related to their commonly low hydraulic conductivities. In the field, this results in lateral water movement and/or surface runoff, which is difficult to simulate in lysimeters. The Lanna clay soil, however, has measured subsoil conductivities of 30 to 100 mm h^{-1} (Jarvis *et al.*, 1991) and horizontal water flows are therefore unlikely to occur.

PREPARATION AND INSTALLATION IN THE LYSIMETER STATION

After collecting the soils, the lysimeters are brought to the laboratory and ca. 0.1 m of soil at the base of the soil columns is removed. This soil is replaced with a nylon mesh followed by a drainage gravel layer, an inert porous sheet, and a fiberglass lid which is screwed onto the inside of the casing wall. Five holes (0.01 m diam.) are drilled in each bottom lid to provide

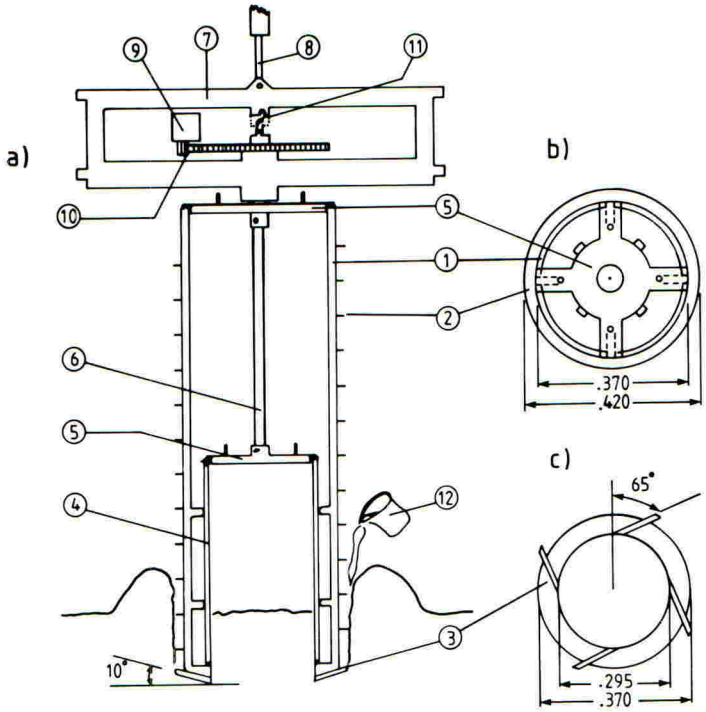

Fig. 1. a) Schematic diagram of soil drill with which the monoliths are collected. The figure shows: (1) cylindrical steel cylinder; (2) auger planes; (3) cutting teeth; (4) plastic casing; (5) cross couplings; (6) extension rod; (7) ram; (8) hydraulic piston; (9) hydraulic motor; (10) transmission; (11) clutch; and (12) water lubrication. b) Upper end of the steel cylinder mounted on the hydraulic ram with four pins ejected from the cross-shaped holder. c) Cutting head with four mounted cutting teeth. All dimensions are in metres (from Persson & Bergström, 1991).

free drainage. Free drainage is considered to be appropriate for this type of lysimeter, since the soil columns are at least 1 m deep. The water-saturated zone formed at the bottom of the profiles is therefore not likely to alter the moisture conditions in the upper half-meter of soil.

The lysimeters are placed in permanently installed pipes inserted in the soil (Fig. 2) at the lysimeter station in Uppsala. Placement is usually done so that replicated lysimeters have the same distance to the collection points. The inside diameter of the pipes is the same as the outside diameter of the lysimeter casing, which minimizes any air gaps around the casing. To make certain, a bead of silicone adhesive is placed around the upper casing wall to prevent air fluxes around it. A fiberglass cap (Fig. 2) is also screwed onto the upper edge of the casing to protect the wall-gap-wall area from rainfall. When installed in the pipes, the

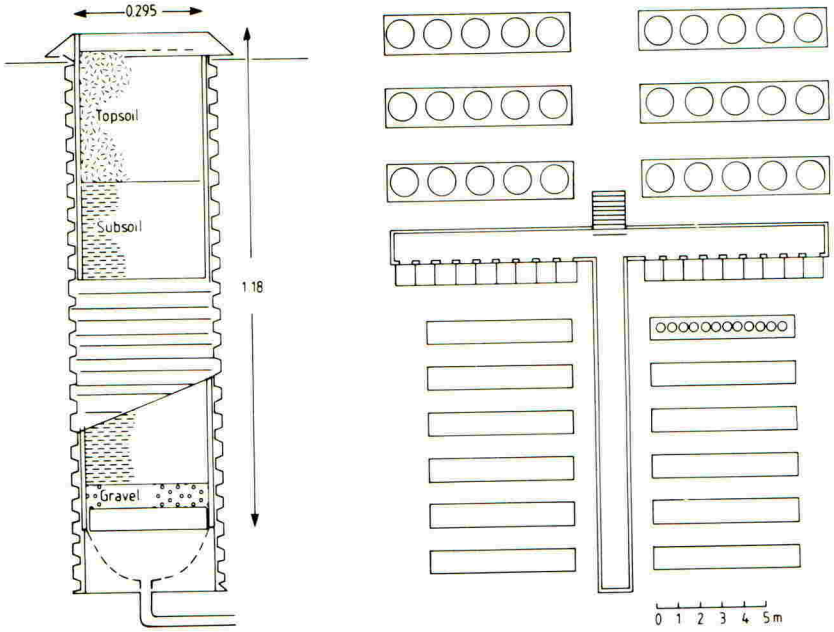

Fig. 2. Lysimeter placed in a belowground pipe (*left*). Layout of the lysimeter station showing 12 monoliths and 30, 1.2-m repacked lysimeters which are not discussed here (*right*). All rows contain lysimeters (not shown in the figure). Dimensions are given in metres (from Bergström & Johansson, 1991).

lysimeter casings stand on bowl-shaped collectors (Fig. 2) connected to an underground station via plastic pipes (polyethylene). The installation of lysimeters in pipes facilitates their removal and replacement. To minimize drifting of snow and to ensure equal precipitation on all lysimeters, the top of the station is only 0.4 m above the soil surface. The station was built to allow installation of 144 lysimeters (Fig. 2) of the type described here.

MANAGEMENT AND EXPERIMENTAL TREATMENTS

All management practices are performed in order to mirror actual field conditions as closely as possible. This includes pesticide spraying techniques, irrigation treatments, fertilization rates and crop cultivation.

A couple of weeks before starting a pesticide dissipation study, the soils are watered until leachate is observed at the lysimeter bottoms. This is done to ensure that the soils are at field capacity shortly before the start of an experiment. It is perhaps relatively uncommon for the soil water content to be at this degree of saturation so close to spraying; however, such a

starting point contributes to standardization and improves the possibilities to compare different experiments and compounds.

In general, spring-sown barley (*Hordeum distichum* L.) or wheat (*Tritium aestivum* L.) are used as standard test crops, since they are grown in most agricultural areas in Sweden. However, special consideration has to be given to those pesticides which are only used for specific crops. Fertilization, seed bed preparation, sowing, harvest, and "ploughing" (i.e. digging down to ca. 0.2 m depth) is carried out at times normal for the Uppsala region. Pesticide applications are carried out when the crop has reached the phenological stage normally sprayed in practice; for barley usually at GS21-25 (Tottman, 1987). Spray volumes and drop sizes roughly corresponding with those used under practical conditions are obtained with a small-plot sprayer (Bergström *et al.*, 1990) and a spray volume of 2.74 ml per lysimeter (400 l ha^{-1}). In addition to normal application rates of pesticides, double doses are also commonly applied to gain knowledge about the leaching of accidently high pesticide levels.

In addition to applying a pesticide, a tracer is also applied on the monoliths to gain some insight into the pathways and mechanisms of water movement in the soils. It could be either a radio tracer (e.g. ^{36}Cl or tritiated water) or an unlabeled salt, such as KBr. In general, we use 37 kBq of ^{36}Cl dissolved in 2 ml of distilled water, which is applied by dropping the solution with a syringe as evenly as possible over the soil surface.

Because the amount of precipitation during a single year may deviate greatly from the long-term average values for the study area, supplemental watering is often needed. We use two irrigation treatments in standardized leaching tests, often referred to as "average" and "worst-case" precipitation. Records of cumulative precipitation are compared with the average for the Uppsala region (554 mm yr^{-1}) and the highest precipitation recorded in the region during the last 75 yr (715 mm yr^{-1}). In both cases, any calculated deficit is compensated for by watering. Watering is performed with a falling-head device allowing individual treatment of each lysimeter. Thirty drip tubes (0.5 mm i.d.) are connected to a water reservoir with the cut ends extending through holes in a round plastic plate which has the same area as the lysimeter surface. The distribution of the tubes over the plate is done to optimize the distribution of water drops over the soil surface. The plastic plate is put on top of a 0.6 m long plexiglass pipe (0.29 m i.d.), to allow watering on a full grown crop. The watering intensity is regulated with a magnetic valve between the water reservoir and the drip tubes. Each watering event is spread out over a period of 2 to 6 h each time (giving intensities <4 mm h^{-1}) to simulate natural rainfall and prevent ponding.

All soils and experimental treatments are replicated, usually three times. It has been shown that the variation in pesticide loads in leachate between replicate lysimeters may be considerable, mainly due to variation in pesticide concentrations and to a lesser extent to variation in leachate volumes between replicates (Bergström & Jarvis, 1992). This suggests that there is a larger spatial variability in soil properties affecting

adsorption and degradation of the compounds than those regulating water storage and flow paths. However, regardless of the causes of variation in pesticide leaching, it is quite clear that we need replicate lysimeters in a study such as outlined here, despite the large increase in costs that this introduces.

LEACHATE SAMPLING

Water draining through the lysimeters is collected in glass sampling bottles placed in the underground measuring station. The bottles are usually weighed weekly to determine the leachate volume. Subsamples are then taken from the accumulated leachate for chemical analysis. However, during periods of heavy rain and during snowmelt, a more intensive sampling schedule is used. For spring-applied pesticides, water sampling continues at least until the next cropping season. For some persistent pesticides, sampling continues for two years after application. It is notable that, under climatic conditions typical for the Uppsala region, a two-year period is normally required to obtain a volume of drainage from a 1-m column corresponding with one pore volume. All bottles in which water is sampled or stored are washed repeatedly with distilled water and ethanol (95 %) prior to their being used to collect lysimeter leachate. If the water samples are not analyzed immediately after collection, they are stored deep frozen to inhibit microbial activity.

Measurements of the temporal depth distribution of a pesticide in soil provide useful information that complements the knowledge gained in leaching studies. This can be done by either destructively collecting samples from various layers of the soil profile, or by collecting water at different depths in the unsaturated zone by use of porous suction probes. However, the first method can only be used at the end of the experiment, whereas water samples may be collected by suction probes throughout the entire experimental period. Both methods have been used in our lysimeter studies, but not routinely. In some studies, soil samples have also been taken in the field from which the monoliths were collected (both systems sprayed with the same pesticide)(Bergström *et al.*, 1990; Bergström *et al.*, 1991). It is not often possible to conduct an intensive field soil sampling program on a regular basis, as a complement to lysimeter measurements. However, whenever feasible, it is certainly highly recommended.

ACKNOWLEDGEMENTS

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FACILITIES FOR THE EXAMINATION OF THE DEGRADATION AND DISTRIBUTION OF CHEMICAL COMPOUNDS IN SECTIONS OF TERRESTRIAL ECOSYSTEMS

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ABSTRACT

Three different lysimeter systems are presented which in construction and function are so matched that they can provide answers to the most important questions on the distribution, degradation and activity of chemical substances in agricultural ecosystems.

Large-scale lysimeters combined in one station (soil core: diameter 113 cm, depth 110 to 120 cm) are used to obtain the substance specific data on distribution, degradation and residues which are required during the registration procedure for plant protection products.
The technically simpler standard lysimeters (soil core: sectional area 48.2 cm x 48.2 cm, depth 65 cm), combined in batteries, are mostly used for series of studies to provide information on the effects of various factors - e.g. application rate and soil type on the degradation and distribution behaviour of active substances in soils.
The closed lysimeter system (soil core: diameter 71 cm, depth 50 cm) enables quantitative analytical investigations in particular of sections of agricultural ecosystems and therefore can be used to study the partition, accumulation and degradation processes. In this way it is possible to determine the quantities of test substance and/or its metabolites, which volatilize from the topsoil and/or the foliage into the atmosphere.

INTRODUCTION

The Biosciences Group of the NATEC Institute, Hamburg, has been performing studies on the biotic and abiotic degradation of chemical substances in soils, sediments and sludges for approximately 20 years. These studies, which have been generally concerned with the fulfilment of legal requirements, were complemented from the beginning with other studies providing information on the fate and on the compartmentalisation of substances in terrestrial and aquatic-terrestrial ecosystems together with the range of their ecotoxicological effects.
During this work special facilities, techniques and analytical procedures were developed, which are particularly suited to the practical testing of the degradation and distribution behaviour of problem substances such as those used for crop protection in agricultural soils.

Both theory and practical experience have demonstrated that under certain circumstances biocides used in agriculture or their metabolites may migrate through the topsoil and the subsoil strata into the ground water, endangering drinking water supplies. Also, if used repeatedly, pesticides and/or their biologically active metabolites may accumulate in the topsoil and adjacent areas, affecting both the microflora and soil animals.
There is also a risk that significant amounts of the parent compound and/or of the often very polar secondary metabolites will bind irreversibly to the topsoil and subsoil strata, leading to a progressive general chemical pollution of agricultural soil.
Therefore, the registration authorities require that prior to registration, the degradation and percolation behaviour in soil of all active substances destined for use as pesticides in agriculture, forestry and horticulture are systematically investigated.

Either field tests or lysimeter tests may be used to fulfil these requirements. The practical performance of the appropriate field tests, however, involves significant technical and generally also analytical difficulties which can compromise the quality of the results. There is, for instance, a particular problem in capturing completely the drainage water from the treated test area, before it reaches the ground water and is diluted. In many cases, too, sufficiently sensitive analytical methods are lacking for the detection and measurement of the unaltered active compound and/or its metabolites in the drainage water and in the soil.
In contrast, lysimeter studies generally give defined, valid and interpretable results. This applies particularly, when large-scale lysimeters of an appropriate design and containing mature soil cores are available to investigate the degradation and percolation behaviour and when, in addition, the test substance is available in a radiolabelled form.

Three different lysimeter systems form part of the test facilities developed by us, which in spite of markedly differing characteristics provide all the requirements for a proper examination of the degradation and mobility behaviour of crop protection products in intact soils. The structure and function of the lysimeter systems are described in the following sections.

EXPERIMENTAL EQUIPMENT AND PRINCIPLE OF STUDY

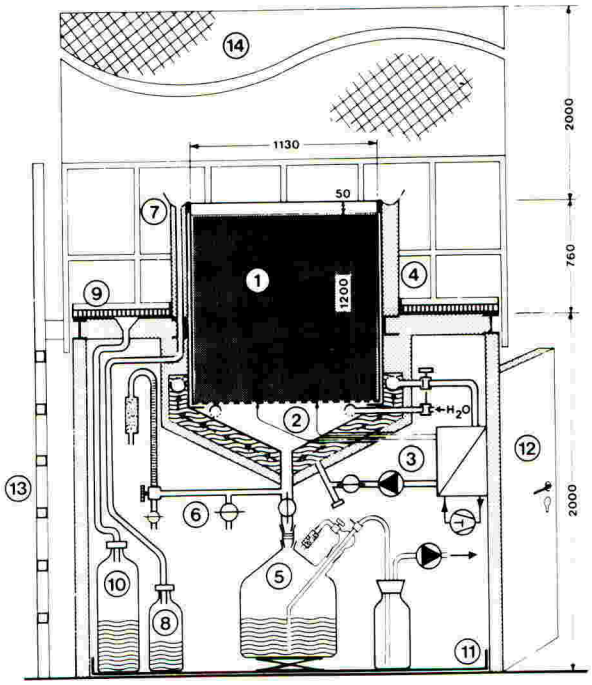
Large-scale Lysimeters

These comply with the BBA Guideline Part IV, 4-3 (1990) and its modification (Schinkel, K., 1991).

Structural features:

The lysimeter station is composed of a row of identical, separate, easily manipulated experimental units. Each unit

consists of two structurally and functionally identical large-scale lysimeters, thus meeting the requirements of the authorities that every lysimeter study should be performed in duplicate. The main structional features of each large-scale lysimeter integrated into the testing equipment can be seen in figure 1.



Explanations:

1 Lysimeter unit containing an intact soil core
2 Stationary steel housing with closable collecting funnel for percolated water
3 Automatic temperature-regulation system for collecting-funnel and bottom of soil core(e.g. +8°C)
4 Thermal/ cold insulation for stationary steel housing and substructure
5 Percolated water receptacle with flexible connector and lifting system
6 Fittings(including water-level indicator) for simulation of ground- water level
7 Collecting gutter for splashed rainwater with down-pipe
8 Receptacle for splashed rainwater
9 Working platform with gratings, collecting basin and down-pipe for rainwater
10 Rainwater receptacle
11 Safety basin
12 Access to substructure
13 Ladder providing access to the working platform
14 Bird- net

FIGURE 1: Large-scale Lysimeter (cross section)

Each lysimeter consists of a central, cylindrical stainless-steel tank (stationary steel housing; internal diameter 114.2 cm, height of cylindrical section 125.0 cm, height of funnel-section 25.0 cm (< 25°)) with a funnel-shaped section at the bottom. The cylinder is used to accomodate the undisturbed soil core (see below) and features a closable discharge valve for the percolated water at its lowest point.
The exterior of the cylindrical stainless-steel tank is completely surrounded by a layer of thermal insulation approximately 12 cm thick and is securely mounted in the steel structure holding the testing equipment. The lower funnel-shaped section of the tank features, in addition to the drainage nozzle, two closable pipes, one of which is connected to a water supply, while the other is connected to a water-level indicator. Using this system, the funnel-shaped section of the lysimeter can be filled in prolonged dry periods with a specific volume of water thus creating a controlled artificial ground water environment in the soil core. This allows simulation of capillary ascent of water during dry periods,

thereby preventing the formation of deep cracks in the soil core, which could possibly lead to unrepresentative results. In compliance with the BBA Guideline, the surface of the soil core is artificially irrigated during dry periods. A sprinkler system, featuring an adjustable water supply system, is fitted above each lysimeter for this purpose.

The gap between the stationary steel housing and the soil cylinder is sealed with a rubber gasket to exclude the possibility of normal rain water or supplemental irrigation water reaching the percolated water.

Both for experimental reasons and to comply with official regulations on the handling of non-enclosed radioactive materials, the testing equipment or the individual lysimeter is also equipped with further technical features. Each lysimeter, for instance, features a so-called overflow channel (collecting gutter for splashed rainwater), which is welded to the top of the stationary steel housing.In case of sudden heavy rainfall, this routes the overflowing water complete with the entrained contaminated soil particles via a down-pipe into a separate collecting receptacle. The working platform, consisting of grid plates and mounted at mid-height around each lysimeter, is also fitted across its entire area with a collecting basin for possible spilled radioactive material, which can also be flushed via a down-pipe into a separate collecting vessel. Both lysimeters contained in the testing equipment are mounted in floor basins constructed of stainless steel, in order to ensure safety even in case of unlikely occurrences such as a sudden leak in the drainage nozzle for seepage water or in the system for simulation of the ground water level.

In contrast to the upper section of the testing equipment, which is continuously exposed to the weather prevailing at the test location, the lower half of the equipment is located in a closable room, which is insulated to protect it against heat in summer and cold in winter, and which is conditioned to approximately + 8 °C. Additionally a separate, automatic temperature control system ensures that the temperature in the collection funnel for the percolated water and in the base of the soil core is maintained at this temperature which corresponds with the approximate annual average found in Central Europe at a depth of 125 cm in the soil.

Undisturbed soil cores and soil characteristics:

The soil cores used in these lysimeter studies have diameters of 113 cm and depths of 110 to 120 cm. They are mainly taken from a representative field specified by the appropriate authority.

The soil can be described as follows: The surface soil down to the depth of approximately 50 cm consists of light loamy sand with a low humus content. The deeper layers are virtually pure sand. A summary of typical soil parameters is shown in Table 1.

TABLE 1: Characterisation of undisturbed soil cores usually used in the lysimeter studies

Soil parameter		Depth of soil samples [cm]					
		0 - 25	25 - 50	50 - 75	75 - 100	100 -125	125 - 150
	Particle size	Distribution of particle size [%] (sieve analysis)					
Clay	< 0.002 mm	2.9	2.6	1.3	Σ 0.5	n.d.	Σ 0.3
Silt	0.002 - 0.006 mm	3.7	2.0	0.2			
	0.006 - 0.020 mm	4.1	3.1	0.9			
	0.020 - 0.063 mm	12.9	8.4	4.0			
Sand	0.063 - 0.200 mm	13.9	11.1	18.4	9.2	6.9	17.0
	0.200 - 0.600 mm	53.6	63.9	69.0	74.5	81.5	74.4
	0.600 - 2.000 mm	8.9	8.9	6.2	15.8	11.6	8.3
Microb. biomass [mg C/100 g dry soil]		18.0	4.1	0.0	0.0	0.0	0.0
Organic carbon [%] in dry soil		1.31	0.59	0.16	0.04	0.02	0.02
Max. water capacity [% by wt.] rel to dry soil		33.5	30.8	24.9	21.8	13.8	20.0
pH value (0.01 M $CaCl_2$ solution)		6.1	6.2	6.3	6.3	6.3	6.3

The soil cores are collected using the following, standardized procedure: A hollow stainless-steel cylinder (internal diameter 113 cm, height 125 cm), the jacket of which takes the form of a cutting-edge at one end, is placed in position on the surface of the soil with the cutting-edge in contact with the soil. The top of the cylinder is then covered with a round plywood lid approximately 15 cm thick. This lid is grooved to accomodate the upper edge of the cylinder jacket. The lid serves as the base for an excavator which drives the cylinder vertically into the soil. Following this, the soil is excavated in a semi-circle around the embedded steel cylinder and a hydraulic unit used to insert a perforated stainless steel plate below the soil core enclosed in the cylinder. This perforated plate has a diameter of 112 cm and is thus slightly smaller than the internal diameter of the driven cylinder. Following complete exposure of the driven cylinder, four 140 cm long mountings consisting of iron bands are placed vertically in position on the cylinder wall in diametrically opposed pairs and their U-shaped ends engaged under the cylinder jacket and the perforated plate. The four mountings, secured by a clamp, are bolted above the cylinder to a cross-beam. The cross-beam is then connected to a hydraulic hoist, and the cylinder, together with the intact soil core, is raised out of the ground and placed on a firm flat surface.

Pressure is then exerted on the upper edge of the cylinder jacket in order to lower it into the U-shaped recesses in the mountings, thus simultaneously raising the perforated plate and the soil core approximately 3 cm within the cylinder. The

driven cylinder is then raised again, complete with the soil core, and iron bands are inserted in the four openings now accessible in the lower sector of the cylinder jacket. The bands are bolted to the centre of the perforated plate to form a bracing system which supports the soil core. The four outer mountings are then replaced by a support system which is connected only to the upper edge of the cylinder jacket and which makes possible transportation of the enclosed soil core to the testing site.

Investigations have demonstrated that this procedure does not damage the soil cores and that the soil characteristics typical of the location are preserved. Further details are given by Figge et al. (1982) and (1985).

Working procedure (principle):

The two stationary steel housings for soil cores are thoroughly cleansed by means of washing and rinsing sequences to remove dirt and possible traces of active ingredients which may otherwise have remained from previous studies. They are equipped with all additional accessories such as vessels for the collection of leachates, and then tested for correct functioning.
Upon completion of this preparatory work, two undisturbed soil cores (see above) are transferred complete with the sample-taking columns from the field to the testing equipment and placed in the cleansed lysimeter unit.
The vegetation (weeds) is manually cleared from the surfaces of the two soil cores, which are then uniformly irrigated with deionized water until clearly discernable quantities of percolation water begin to leave the cores. The soil cores thus "soaked" are protected against further, natural rainfall by means of covers and are kept undisturbed under these conditions for three days. Thereafter the covers are removed and both soil cores maintained for a further 2 months under the natural weather conditions pertaining at the study site.
After this the topsoils of both soil cores are cultivated manually following the principles of "Good Agricultural Practice" and sown with selected species of grain or seeds of plants typical for Central Europe in spring and autumn, respectively.

The further stages in the progress of the lysimeter studies and their duration depend principally upon whether the active ingredient (test substance) being investigated is to be applied to an agricultural area only once during a crop rotation, applied during each growing period or have multiple application during one cultivation period (Schinkel, K., 1991).
If the test substance, for example, is a plant growth regulator which in practice is applied only once before flowering of cereals, the application of the ^{14}C-labelled substance is delayed until the cereals have reached the appropriate stage of growth - usually stage 8.5 (Feekes scale) or stage 37 (Zadox scale) when 100 % flag leaf is visible.

The quantity of test substance to be applied at time t_o of the study to each of the 1.0 m^2 surface areas of the soil cores containing cereals is calculated beforehand on the basis of the maximum amount of active substance recommended in practice. The quantity of test substance calculated in this way is introduced, in ^{14}C-labelled form, into the storage tank of a spray unit, dissolved in a specified volume of water (which also contains additives as appropriate) by stirring vigorously and then immediately applied uniformly to the cereal canopy on the soil core (time t_o of the experiment).
The second soil core is sprayed likewise with ^{14}C-labelled test substance at the same time. In order to establish the precise quantities of radioactivity and test substance applied to the vegetation and surface of the two soil cores at time t_o, the residual radioactivity, remaining in the spray units is measured.

The soil cores thus treated with ^{14}C-labelled test substance are kept for 2 or 3 years under the natural weather conditions prevailing in the Hamburg area. All the meteorological data necessary are provided to us by the "Deutscher Wetterdienst" (German Meteorological Service) from its Hamburg-St. Pauli weather centre; precipitation and temperature are, nonetheless, also measured directly at the study site.
Particular care is taken to ensure that the collection vessels for percolation water are always replaced throughout the entire 2 or 3 year study period on a fixed time schedule and that the contents of the old vessels are completely registered and immediately forwarded for analysis (measurement of radioactivity, intact test substance and main metabolite).

Additional artificial irrigation is applied at times of low precipitation to ensure that the annual precipitation is not less than 800 mm so that the conditions typical for potential migration of the test substance and/or its metabolites into deeper-lying soil strata and for their exit in the percolation water are maintained.

Figure 2 clearly shows that the results obtained under these conditions for a ^{14}C-labelled test substance in two lysimeters containing similar soil cores are in good general agreement with each other.

In the late summer of the first trial year the cereals are harvested separately from each of the soil cores, and each crop is then separated into stems and ears. The ears are then further separated, by threshing, into grain and chaff. The plant material is air-dried after which aliquots are removed for measurement of radioactivity. Remaining samples of stems, chaff and grain are reserved for future analysis.

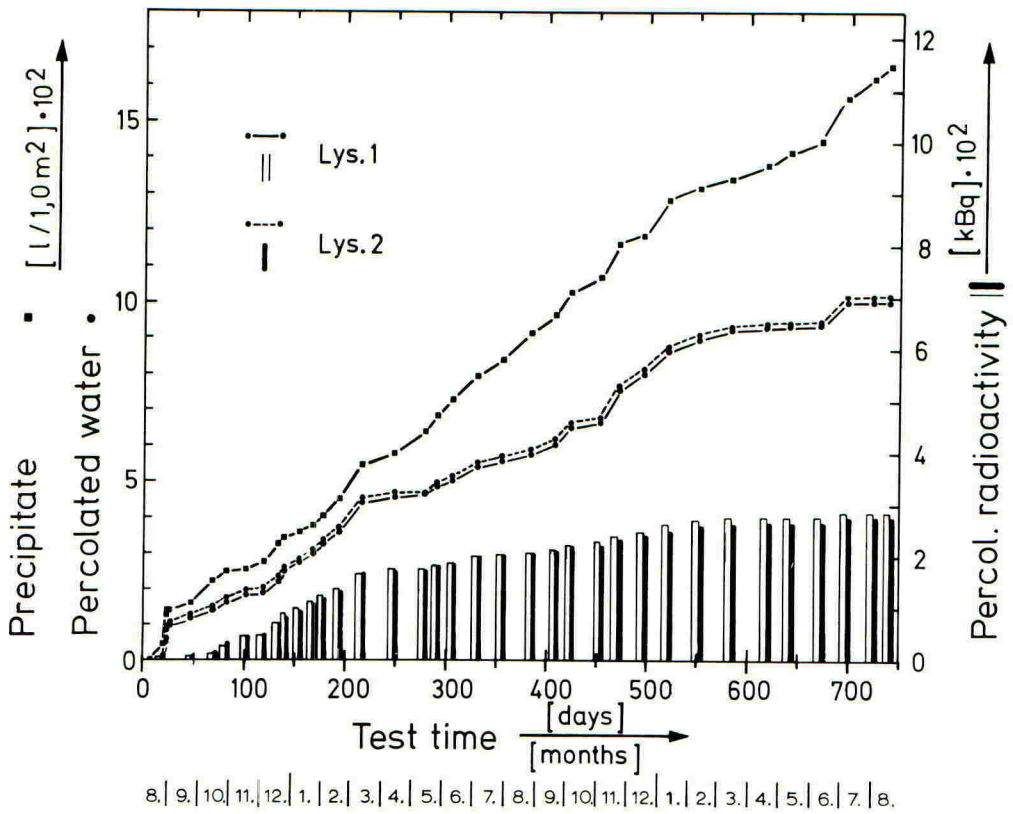


FIGURE 2: The cumulative quantities of precipitation, percolated water and radioactivity which occurred in the course of a duplicate lysimeter study on a ^{14}C-labelled test subsance

Following the harvest the topsoils of both soil cores remain fallow until the following spring. The topsoil is then recultivated as described above and sown with the same or another spring cereal. In the following summer, the ripe crop is harvested and analysed as described above.
Just before the start of these procedures, topsoil samples to a depth of 28 cm are taken at five randomly chosen spots of each soil core using a hollow drilling cylinder. Each of these soil samples is weighed and cut into smaller sections, which are prepared for measurement of radioactivity.
At the end of the investigation, both soil cores are divided into layers of 10 cm thickness and the radioactivity measured.

As can easily be seen from figure 3, the concentration profiles of the ^{14}C-labelled test substance and/or its radioactive metabolites in the topsoils of duplicate cores are also in good general agreement with each other.

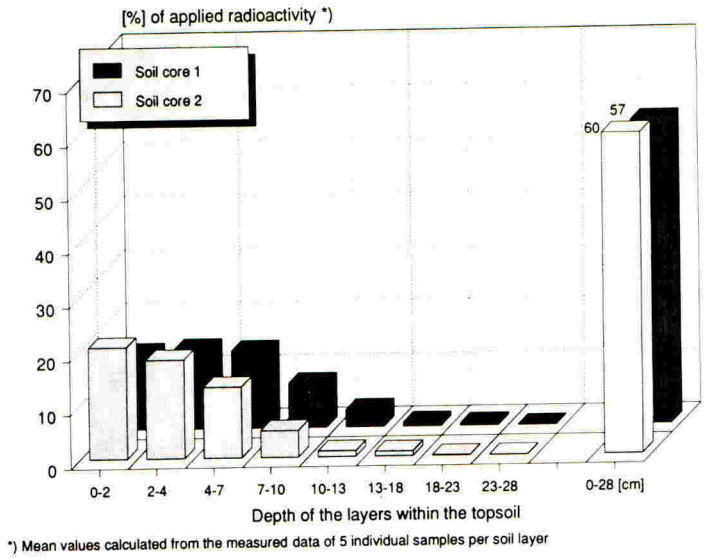


FIGURE 3: Decrease of radioactivity, applied as ^{14}C-labelled test substance, in the topsoils of two duplicate soil cores

Lysimeter Battery

Structural features:

The experimental equipment consists of 8 identical lysimeters, which are arranged in pairs (see figure 4). It is, therefore, particularly suitable for comparative studies - for instance to determine the effect of soil type and rate of application on the transport of active substances into the ground water. It should be noted, however, that the individual lysimeters do not have the dimensions required by BBA Guideline Part IV, 4-3 but are markedly smaller.
Each lysimeter consists of a rectangular stainless steel container open at the top and featuring a funnel section at the bottom (internal dimensions: cross-section 50 cm x 50 cm, height of the column 59 cm). The funnel-shaped section is 8 cm high and has a drainage socket for the leachate at its lowest point. This lysimeter and leachate collection system is firmly enclosed in the steel structure designed to hold eight lysimeters. With the exception of the openings and the lower, funnel-shaped section the lysimeter container is completely enclosed in an approximately 10 cm thick layer of insulating material. The soil cores are inserted into the rectangular container. The soil is collected in steel columns with outside measurements of 49 cm x 49 cm x 75 cm. The collection vessels (glass) for the leachates have a volume of 10 litres. The top surfaces of the soil cores in the lysimeters are continuously exposed to the weather conditions prevailing at the study site, while the lower, funnel-shaped sections of the lysimeters are

located in a lockable chamber, which is insulated against heat (for summer conditions) and cold (for winter conditions).

In addition, instruments are installed at the trial site to measure precipitation and temperature, the two climatic factors particularly relevant to degradation and translocation of active ingredients. This complements the data provided by the "Deutscher Wetterdienst" from its Hamburg-St. Pauli weather centre.

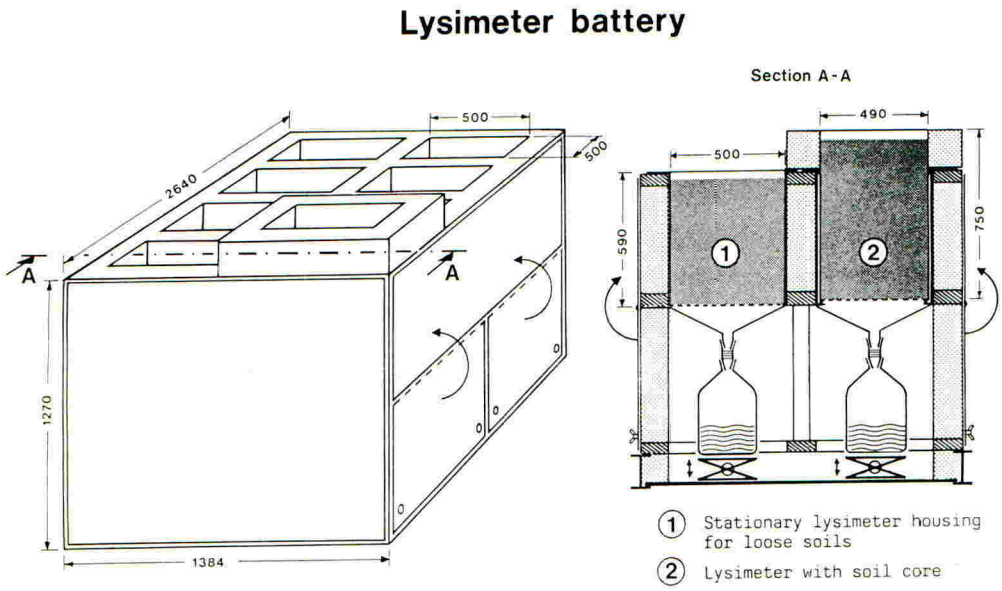


FIGURE 4: Lysimeter battery which is used to accomodate defined quantities of loose soil or the steel inserts containing undisturbed soil cores

Undisturbed soil cores and working procedure:

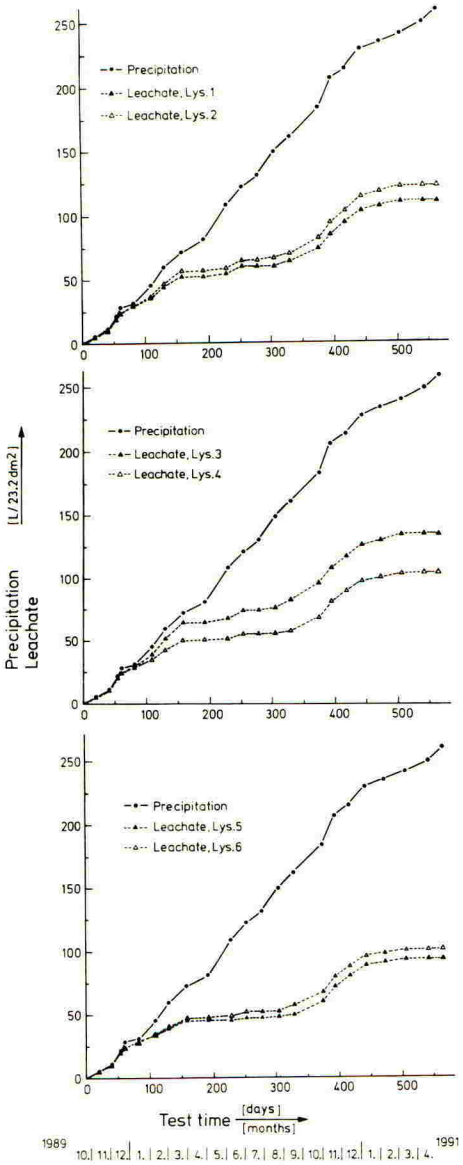
The soil cores proposed for lysimeter studies on the degradation and leaching characteristics of active substances have the following dimensions: sectional area 48.2 cm x 48.2 cm, depth 65 cm and are also taken from fields specified by the appropriate authority. They are collected using the same procedure as for the large-scale cores.

The following trial procedure and evaluation of test data are in accordance with the general principles for conducting lysimeter studies fixed in the BBA Guideline (1990).

Practical example:

It demonstrates the applicability of the lysimeter battery.
Six undisturbed soil cores (compare table 1) with the dimension mentioned above were used in a lysimeter study of a herbicidal active substance - an isoxazolylbenzamide. The single, double and four-fold rate, which was applied to each surface area of

the soil cores in the lysimeters, was based on the application rate of the active substance per hectare for pre-emergence application in winter-cereals. The rainfall during the course of the lysimeter study equals 1140 mm precipitation in 1 1/2 years - including the additional irrigation. During the same period, we collected an average quantity of 110 L (s_e [%] 14.0) of leachate per lysimeter (compare s figure 5).



Analysis of the numerous leachate samples collected at a depth of 65 cm showed that only on one occasion, 110 days after treatment, the active substance and its major metabolite were found in concentrations above the detection limit. The detection limit of the HPLC methods was 0.08 µg active substance or 0.06 µg major metabolite per 1.0 L leachate.

This study shows that the herbicide for the pre-emergence control of broad-leaved weed in winter-cereals and its major metabolite cannot be very mobile in soil profiles. This means that contamination of ground water can be virtually excluded.

The unique occurrence of concentrations of active substance and its major metabolite above the EC drinking water limit of 0.1 µg/L on 110 days after application should be attributed to a very heavy rainstorm just prior to collection of the leachates.

FIGURE 5: Cumulative values of precipitation and leachate which occurred during the course of the leaching study in the lysimeter battery

This strongly suggests that we are dealing with preferential mass flow, rather than with capillary movement through the soil profile. Preferential mass flow occurs when water flows through fissures and macropores in the soil and should therefore be considered a function of the soil characteristics and not a property of the active substance under investigation (Bergström et al., 1990).

This hypothesis was further supported by total absence of traces of active substance and its metabolite in leachate samples collected 21 days later.

Closed Lysimeter System

The closed lysimeter - also known as the plant metabolism box - enables quantitative analytical investigations of agricultural ecosystems or their representative parts. This device has been used successfully in the investigation of active substances with respect to their partition, accumulation and degradation processes.

The part of the ecosystem under investigation can be kept at well defined, chosen, climatic conditions or at the climate equivalent to that outside the test device.

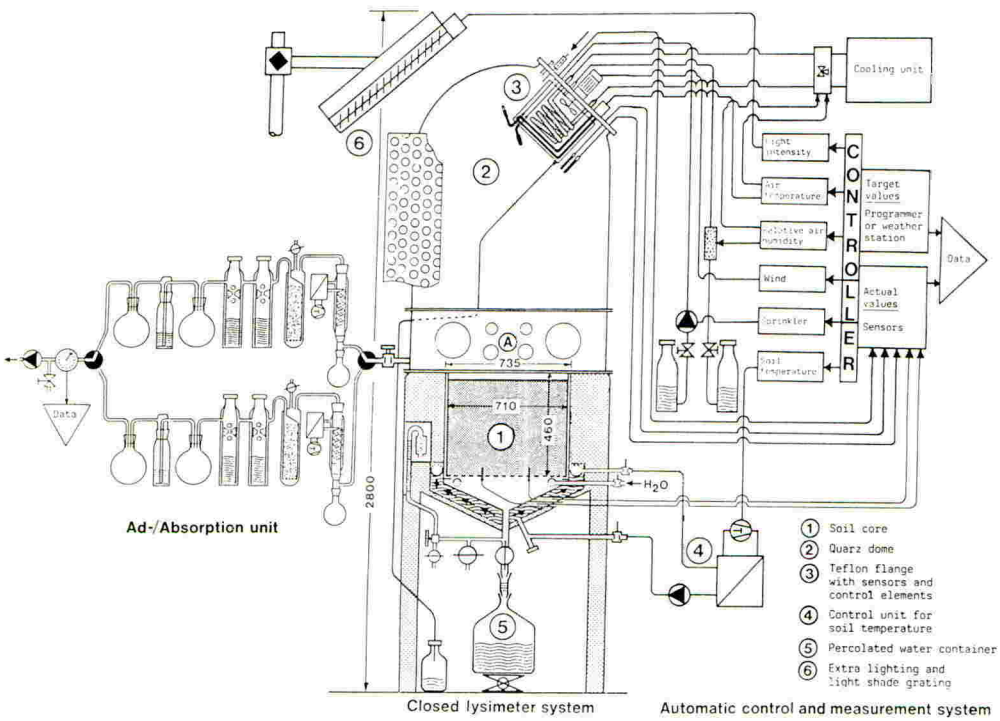


FIGURE 6: Total construction of the close lysimeter system (Plant metabolism box)

The design of the device allows material exchange with the environment only in a controlled manner.

Structional features:

The set-up and function of the plant metabolism box, have been described in detail elsewhere (Figge, K. et al. 1977, 1982, 1983, 1985, 1986), so only the most important features of the test device, shown in figure 6, are described:

A teflon-coated, temperature-regulated steel tank with a bottom grate for accomodating the stainless steel cylinder contains an undisturbed soil core. It also includes a collecting device for percolated water (identical in its technical construction to the large-scale lysimeter already described). The steel tank is fitted above with a quartz dome (quartz cylinder with closable sampling windows and a hemispherical quartz top), having a 96 % transmission for all wavelengths of day- and sunlight, from UV to IR (cylindrical part: diameter 74.5 cm, height 63.5 cm; hemispherical part: height 37.3 cm; total internal volume 585 dm^3).

There is a coordinated air-conditioning system which includes:

- programme units for the nominal time-dependent variation of air temperature, air humidity, intensity of light and wind velocity;
- sensors fitted in the quartz dome and soil core, respectively, for the continuous monitoring and registration of current climatic data, soil temperature as well as soil humidity.
- heating and cooling elements with their external supply installations, ventilator for adjusting air velocity, external suction pumps for attaining the desired flow rate of air, external air humidifier, external illuminating unit with controllable intensity of light and a sprinkler system.

There is an ad-/absorber system for the quantitative removal from the exhaust air stream of volatile fractions of test substance and its metabolites. During the operation of the testing equipment, ambient air is sucked through a coarse filter, a flowmeter, a distribution fitting (at the application flange of the hemispherical quartz top) and a ventilator into the quartz dome, using a diaphragm pump. Subsequently, the air is transported through an outlet pipe (at the lower part of quartz cylinder), followed by a cooling trap, the ad/-absorber system (activated carbon → potash lye (potassium hydroxide, 2x) → paraffin oil (2x)), a gas-meter and regulating valve (flow controller) into the open.

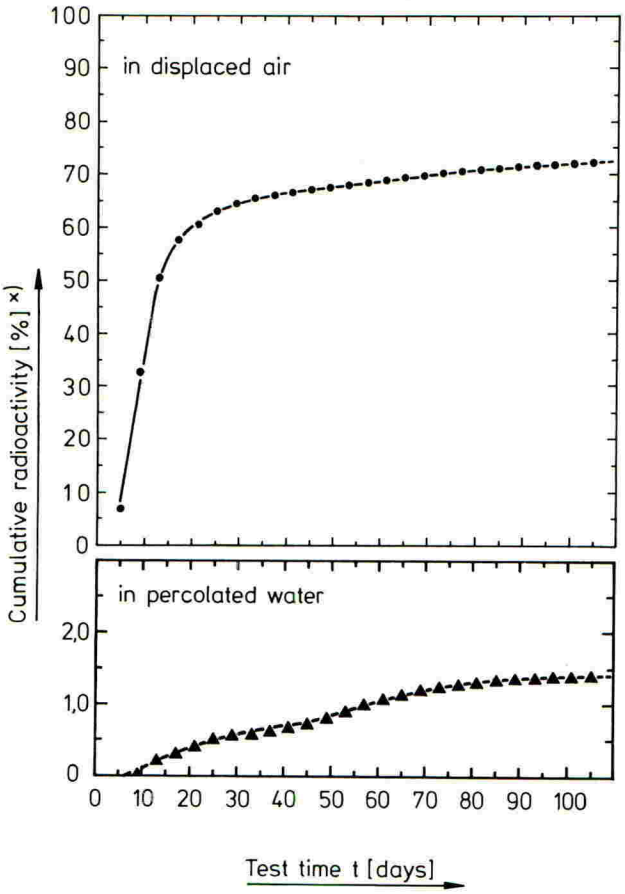
As a result of the interaction between these units (and others not described here) it is possible to maintain the system under exactly defined climatic conditions.

Undisturbed soil core and working procedure:

The technique of obtaining a suitable, undisturbed soil core (diameter 71 cm, depth 50 cm, surface area 40 dm^2) from an agricultural field and its transfer into the plant metabolism box is again practically identical to that used for fitting out the large-scale lysimeters described above.

The various stages in the practical performance of a study in the closed lysimeter system are described by Figge et al. (1982) and (1985).

During the lysimeter study two fundamentally different sets of samples are obtained, 1) samples from the ad-/absorber system and percolated water samples and 2) plants or plant components and soil samples.



x) rel. to total radioactivity applied as ^{14}C-LAS into the standardized ecosystem 'Potato field'

The materials from the ad-/absorber system and the percolating water samples are analyzed at intervals. Analysis of these samples supplies information on the time course (the kinetics) of transformation of the test substance and subsequent products, volatilisation and movement with the percolating water.

As an example figure 7 shows typical results obtained for a mixture of linear alkyl[u-^{14}C]benzenesulfonates (^{14}C-LAS) applied together with digested sewage sludge to the topsoil of an agricultural ecosystem section maintained in a standard climate, typical of the main growing period in Northern Germany (Figge, K. et al. 1989).

FIGURE 7: The cumulative curves of the transfer of radioactivity, applied as ^{14}C-LAS together with digested sewage sludge, from the topsoil of an agricultural ecosystem section into the atmosphere (radioactive CO_2↑) and into the drainage water, as a function of time (Figge, K. et al, 1989)

On completion of the lysimeter study the plants or parts of plants in the test device and the soil or individual soil strata are collected. Analysis of the soil materials gives important information including the distribution of the test substance and/or its metabolites in the soil core. This data when combined with the results mentioned above describes the partition of these substances in the ecosystem section tested (Balance of the test substance applied and its metabolites).

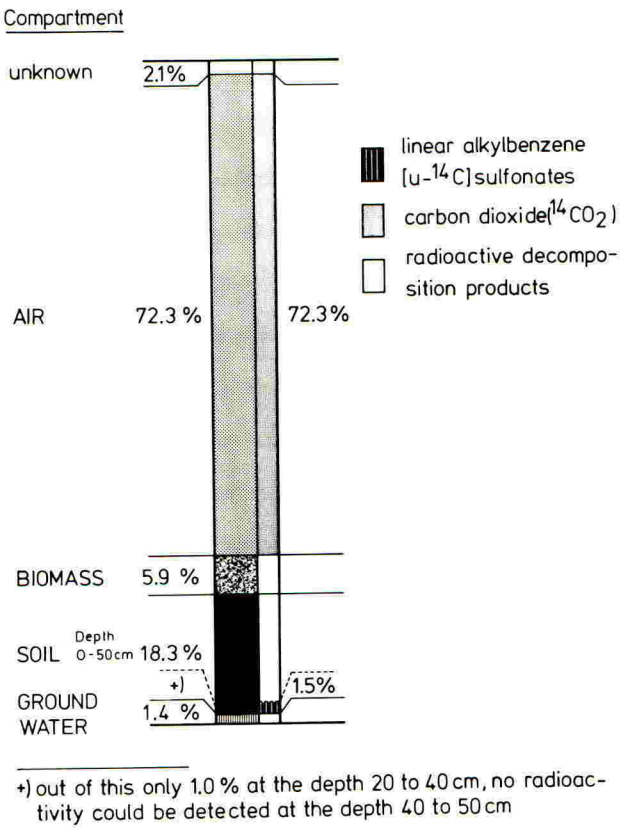


Figure 8 shows a typical example which is directly related to the results presented in figure 7. It demonstrates the proportions in which the ^{14}C-LAS mixture and its metabolites were distributed in the various compartments of the agricultural ecosystem during a period of 106 days.

FIGURE 8: Distribution of ^{14}C-LAS and their radioactive degradation products among the different compartments of the agricultural ecosystem, recorded on the 106th day after application of ^{14}C-LAS contaminated sewage sludge into topsoil (Figge, K. et al. 1989)

SURVEY

Three lysimeter systems each differing in construction and function have been presented. They were developed by us during the last 20 years in response to the increasing scientific and legal requirements, taking into account the relevant practical experience. They were used to examine the distribution, degradation and activity of chemical substances in agricultural ecosystems.

The dimensions and the measuring techniques of the large-scale lysimeters grouped in a lysimeter station conform to the requirements not only of the BBA Guidelines Part IV, 4-3 but also to those of other national and international authorities. Consequently, all the substance specific distribution, degradation and residue data required, for instance according to the BBA Guidelines, for the registration of an active ingredient, can be obtained using the large-scale lysimeters.
In contrast, the lysimeters arranged in batteries are markedly smaller than demanded by the regulations and equipped with a simpler measuring technology. Nevertheless, the general design of the experimental equipment and the working procedures are in accordance with the general principles for conducting lysimeter studies. Therefore, these batteries of adjacent pairs of lysimeters are useful for preliminary studies conducted as series of comparative trials to obtain information on the effects of various factors (e.g. application rate and soil type) on the degradation and translocation behaviour of substances in soil.
The characteristic property of the closed lysimeter system (plant metabolism box) is that a mass balance of the test substance can be obtained. The construction of the test system allows material exchange with the environment only in controlled ways. Therefore, using the closed lysimeter system it is possible to measure the quantities of test substance and/or its metabolites which are transferred from the topsoil and/or the foliage into the atmosphere under defined climatic conditions (volatility). The advantages of the plant metabolism box are on the one hand the scientific requirement for clearness and reproducibility of the experimental conditions is met, on the other hand the ecosystems themselves or their representative parts can be investigated. This guarantees that the tests carried out are scientifically exact as well as near reality.

Three test systems for performing lysimeter studies and which complement each other well are therefore available. Together they provide a solid basis for the extensive examination of the distribution, degradation and activity of chemical substances in agricultural ecosystems.

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