FIELD MEASUREMENTS OF GROUNDWATER POLLUTION FROM AGRICULTURAL LAND USE

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Abstract

This study was carried out in a problem area located to the northeast of Vienna. Several devices were installed for collecting water samples from the soil profile to measure nitrate concentration: suction cups, soil-water samplers, tensiometers and small lysimeters. Measurements of N leaching from four levels of fertilizer application were made at Gross Enzersdorf under irrigated wheat using suction cups and lysimeters. In order to determine fertilizer-N uptake by plants and the amounts retained in the soil and leached, ^{15}N-enriched fertilizer was applied to micro-plots. The nitrate concentrations below the root zone were measured for winter wheat followed by a cover crop, using suction cups. Soil-water contents were measured in the soil profile with a neutron probe and gypsum blocks, and suctions were measured with tensiometers at four depths. The yields of crops together with total N in grain and straw from fertilizer and soil were calculated. Also presented are data on the mineralization, immobilization and actual fertilizer used by the crops. Winter wheat took up between 27% and 44% of the applied fertilizer. The storage of fertilizer N in soil ranged between 22% and 36%, and only a small fraction was leached.

1. INTRODUCTION

It has been widely reported that water resources are prone to contamination from point and diffuse sources within agricultural watersheds. Non-point-source agricultural pollution of groundwater has become a threat to the environment over the past 30 years [1–3]. The relationship between N pollution and agricultural practices is largely uncontested except for some controversy. Nitrogen in the form of nitrate is a fundamentally important nutrient for plants. High rates of mineralization and excessive fertilization increase the amount of N leaching into the soil profile. Nitrate is very soluble and therefore moves with water in the soil from agricultural areas to pollute groundwater. Nitrogen transformations in soil are complex and dynamic, and have the potential to cause substantial N-losses not only via leaching, but also as a result of ammonia volatilization, and denitrification.

For some years, scientists at the Institute for Hydraulics and Rural Water Management, University of Agricultural Sciences, Vienna, have been studying the problem of N leaching in agricultural areas. Current research encompasses shallow and deep soils with various degrees of cultivation, and various N-fertilizer carriers (e.g. mineral fertilizers, liquid manure, sewage sludge). Simple field-testing and measurement sites have been set up at various locations where groundwater samples are collected at different depths to determine the extent of N leaching into groundwater.

To measure the water content of soil profiles, several devices are available, including gypsum blocks and neutron probes. Similarly, technologies have been developed to measure pollution of groundwater by monitoring nitrate concentration. These provide information on the movement of N in and from agricultural areas. As nitrate in groundwater can come from fertilizer application and/or soil mineralization, fertilizers are often labelled with distinguishing isotopes. Cover crops planted during fallow seasons are also important users and contributors of N; they assimilate and store N, and during subsequent tillage are incorporated into the soil and slowly release N by mineralization. Considering these aspects, the current research project was undertaken with the objective of measuring and comparing various soil-water content and soil-water sampling devices. Other objectives included measuring nitrate concentration below the root zone, together with determining the fate of fertilizer applied at four rates to winter wheat followed by a cover crop.

Over the past several years, concern has been growing over the maintenance of quality of Austria's vast water resources [4]. On the plains, where groundwater is a major source of drinking water, nitrate concentrations have increased dramatically in the past four decades. Among the various land uses causing groundwater pollution, agriculture is generally recognized to be a chief contributor. The

TABLE I. GROUNDWATER POLLUTION IN AUSTRIA (BUNDESMINISTERIUM FÜR UMWELT, 1996)

State	Total investigated area		One critical substance above limit		Contaminated area by nitrate	
	km^2	%	km^2	%	km^2	%
Burgenland	1,685	100	1,685	100	1,442	85
Carinthia	898	100	571	63	100	11
Lower Austria	3,039	100	2,025	66	1,909	62
Upper Austria	2,379	100	2,032	85	1,352	56
Salzburg	171	100		0		0
Styria	753	100	559	74	518	68
Tyrol	414	100	101	24		0
Vorarlberg	261	100	216	82		0
Wien	318	100	318	100	318	100
Austria	**9,918**	**100**	**7,507**	**75**	**5,639**	**56**

TABLE II. RATES OF FERTILIZER IN $kg.ha^{-1}$ NITROGEN

Treatments		Unfertilized	Fertilized 100%	Fertilized 150%	Fertilized 200%
Winter wheat	1995/96	0	120	180	240
Cover crop	1996	0	0	0	0
Soybean	1997	0	60	90	120
Winter barley	1997/98	0	120	180	240

pollution in each province is presented in Table I. Components investigated included nitrate, nitrite, ammonium, chloride, phosphate, sodium, potassium, atracine and its metabolites, tetrachlorethen and 1.1 dichlorethen. The government of Austria has forbidden the use of atracine as a pesticide, therefore it was not included in our list of pollutants. Table II presents the total area investigated for pollution control, the area contaminated by at least one of the above mentioned controlled substances and the area contaminated by nitrate, for all nine states of Austria.

In Lower Austria, total groundwater area is about 3,000 km², with 66% contaminated because at least one pollutant was found to be above its threshold value. Out of this, about 62% is contaminated by nitrate only. Table II shows also that groundwater contamination by nitrate has reached serious proportions, which was the main reason the present research was undertaken.

During the last few decades, mechanization has contributed to an intensification in agriculture leading to higher nitrate concentrations in groundwater reserves [5]. In Austria, the limit for nitrate in drinking water has been set at 50 mg NO_3^- L^{-1} [6]. Periodical testing of aquifers has revealed that 17 to 20% are in excess of that limit. Literature and reports on nitrate in aquifers indicate that about half of that pollution is caused by agricultural activities, the other half is contributed by point sources, e.g. business, industry and sewerage [7]. Current pollution is such that for an aquifer of a depth of 25 m (pore volume 0.35) a nitrate concentration of 60 mg L^{-1} would take more than 30 years to fall to 30 mg L^{-1}, if a nitrate-free percolation rate of 200 mm $year^{-1}$ were available [8].

The use of N-fertilizers in Austria increased from 12 kt N in 1946 to 118 kt in 1970. Since 1970, a slow reduction to 103 kt N has occurred [9]. Despite this trend, nitrate concentrations in groundwater have increased with enrichments in organic N in the upper soil layers. The mineralization of organic N to ammonium and, in turn, its nitrification to nitrate add to the effects of fertilization. Leaching of N to the groundwater occurs mainly in the form of nitrate; ammonium is immobile in soils.

The aim of this work was to establish the suitability of four devices for determining soil-water quality, through the measurement of the nitrate content and ^{15}N-content in the sampled soil solutions. The experiment was part of a larger project of sixteen plots, in each of which eight suction cups and one small lysimeter were installed. Twelve of these plots were used in this work for suction-cup/lysimeter comparisons; six plots were equipped also with tensionics, and three contained soil-water samplers.

2. MATERIALS AND METHODS

2.1. Site

The experiment was located in the northeast of Vienna, Austria (48°25'N 16°30'E). The climate diagram shows precipitation and temperature from 1961 to 1990; the average annual precipitation is 551 mm and temperature 9.7°C (Fig. 1). No dry period is predictable, although rain-free intervals of 20 to 40 days may occur once or twice during the growing season [10]. Therefore, irrigation is required for many crops grown in the area.

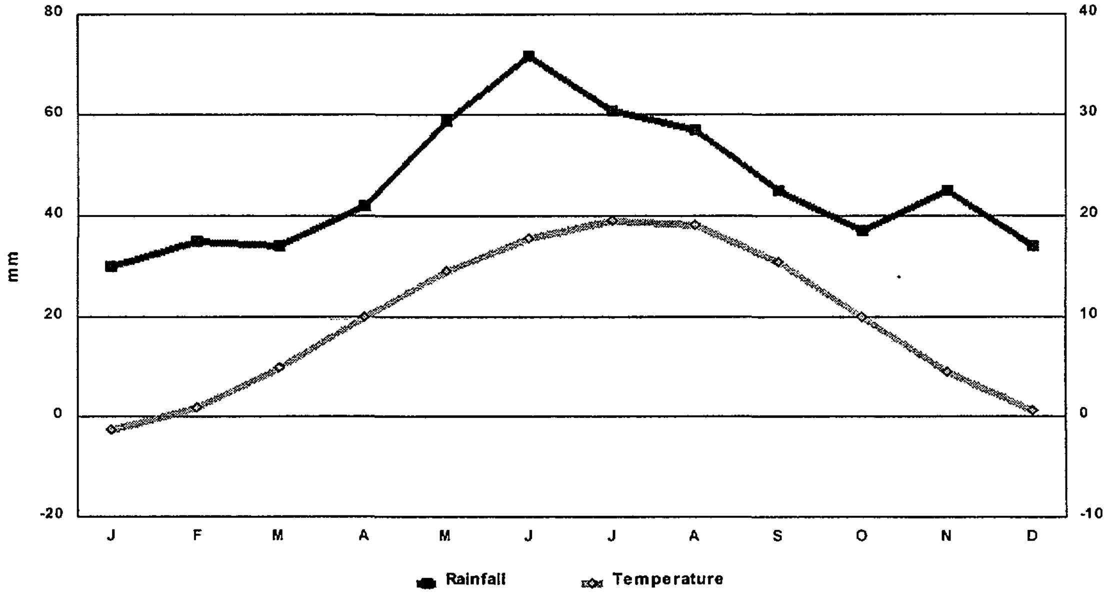

FIG. 1. Climatic diagram of the study area from 1961 to 1990.

2.2. Measuring devices

Soil-moisture determinations were made with tensiometers (tensionics), gypsum blocks, and the neutron probe (SOLO 40). Small lysimeters and suction cups were employed to measure N leaching. In order to eliminate influences of fences or windbreak hedges, the measuring devices were installed at least 7 to 8 m from the edge of the field. The distance from wind-protection appliances was at least 50 m.

The ceramic suction cups had a diameter of 20 mm, a length of 80 mm, and an average pore size of 1.0 to 1.5 µm (Fig. 3a). They were connected with 1-mm diameter tubing, about 10 m in length, to a collecting bottle within a measuring unit [11]. The water samples were translocated to the measuring unit by maintaining continuous suction in the tubes (Fig. 2). Due to the small diameter of these tubes, only about 8 mL of water were stored in each tube at any time. The ceramic suction cups were installed horizontally into undisturbed soil and samples collected weekly. Two suction cups were installed at each location.

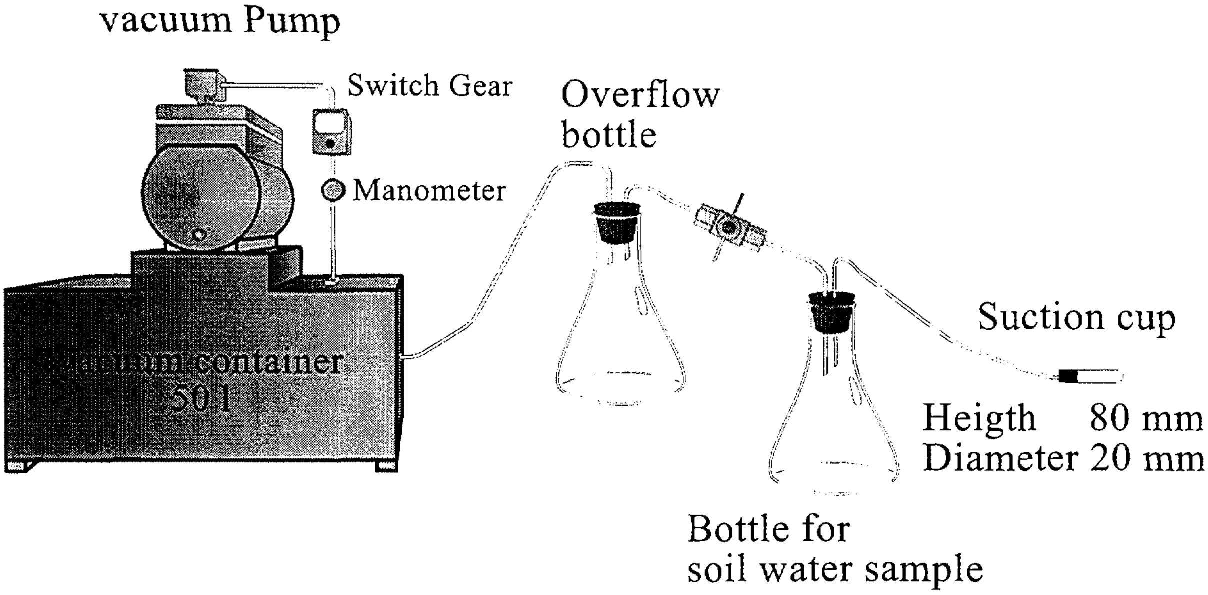

FIG. 2. Suction cup and the vacuum system.

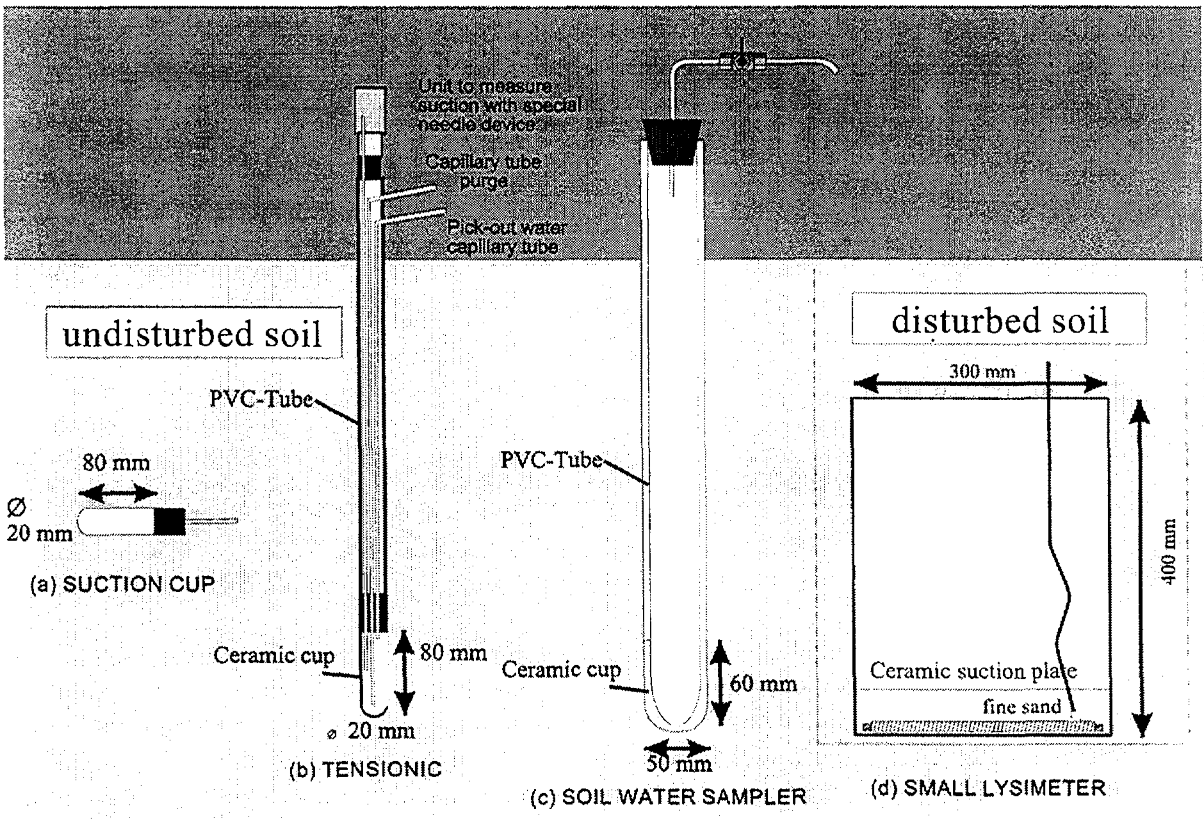

FIG. 3. Devices for measuring suction, percolation and nitrate concentration in the soil.

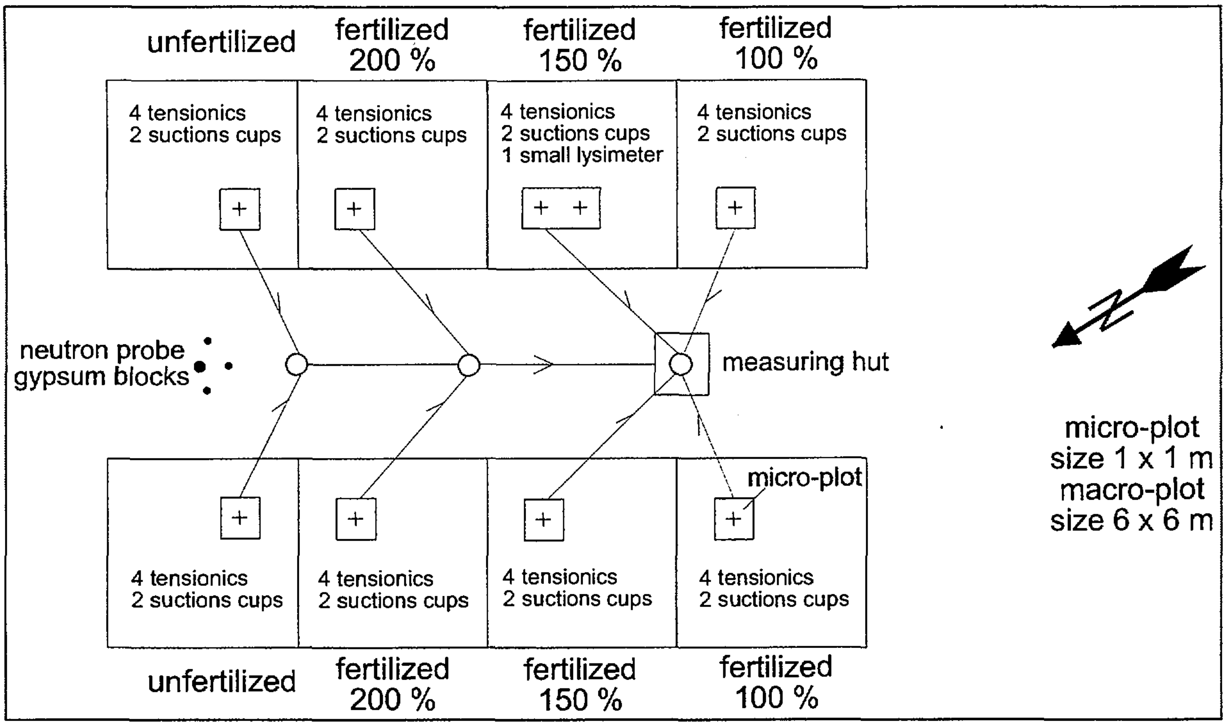

FIG. 4. Plan of the experimental site.

TABLE III. TILLAGE OPERATIONS FROM 1995 TO 1998

Winter wheat 1995 / 96	13. Oct	Planting of wheat	**Soybean 1997**	24. Apr	Row planting
	11. Apr	60 kg/ha N-fertilizer		16. Jun	60 kg/ha N-fertilizer
	09.May	60 kg/ha N-fertilizer		13. May	25 mm Irrigation
	13. Jun	60 mm Irrigation		03. Sep	Harvest
	23. Jul	Harvest	**Winter barley 1997 /98**	23.Sep	Planting of barley
Cover crop	03. Aug	Planting of cover crop		19. Feb	65 kg/ha N-fertilizer
	05. Nov	Incorporation of cover crop		04. May	55 kg/ha N-fertilizer
				25. Jun	Harvest

The tensionics consisted of high-flow ceramic cups, 20 mm in diameter, with a plug containing three capillary tubes sealed with adhesive bonding (Fig. 3b). Two of these tubes reached to the bottom of the ceramic cup, one for the hydraulic load, and the other to extract the solution. The third terminated at a higher level in the cup, for system purging and return to the cup. The porous cups were initially filled with distilled water. The nitrate concentration of the surrounding soil solution is reached by ionic or molecular diffusion usually within 10 days [12, 13]. They were installed in undisturbed soil.

Each soil-water sampler consisted of a PVC tube, diameter 50 mm. A porous ceramic cup, with a 0.2-MPa air-entry value, was attached to one end (Fig. 3c). The other end of the tube contained a stopper with an attached rubber tube to allow removal of the sample. The rubber tube had a clamp to retain suction after evacuation. These were placed also in undisturbed soil.

The small lysimeters, installed at a depth of 105 cm, consisted of a high-flow ceramic suction plate within a PVC tube, diameter 30 cm, height 40 cm, with a closed base. A tube connected the suction plate to the measuring unit where the samples were collected. The suction cups and lysimeters were evacuated with a pump that operates at 0.05 MPa suction, and water samples were collected every week

(Figs. 3d and 5). The 0.05-MPa suction was chosen as the collecting bottles were located about 2 m above the soil surface so, even at field capacity, the suction was sufficient to push water into the sampling bottles.

To measure nitrate concentration, three different types of ceramic cup, i.e. ceramic suction cups, tensionics, and soil-water samplers, were installed. Nitrate concentration was also measured using the small lysimeter. In order to install a suction cup, it was necessary to dig a hole equal to its diameter, which has the advantage of causing minimum soil disturbance. The installation of the small lysimeter [11], which has a diameter of30 cm, requires removing soil layers carefully and returning them in order.

To provide comparative data, ceramic cups were installed at 15, 45, 75 and 105 cm in an apple orchard. To measure percolation, the small lysimeter was installed at 105 cm, belowthe effective root zone of approximately 90 cm depth. Therefore, all the water that percolated below 90 cm was contributing to the groundwater. In order to appraise the effects of the disturbance in the soil structure caused by the installation of the lysimeter, the qualitative analyses of the seepage water collected by the lysimeter and suction cups, which were installed in the undisturbed area, were compared.

Three levels of N fertilizer were applied by fertigation or broadcasting, and nitrate concentraions in the soil profile were determined. Labelled fertilizer (5% ^{15}N a.e.) was applied weekly from mid-April to the end of June 1995 by fertigation at rates of 5 and 10 kg N ha^{-1}, and broadcast on the first and fifth weeks at 20 kg N ha^{-1}. Tensionics require a minimum of 10 days for ionic or molecular diffusion, therefore, the sampling interval was selected as every 14 days [12].

To investigate the efficiency of N-fertilizer application, a project involving winter wheat ('Capo') with four rates of fertilizer application was undertaken at the Institute's experimental site at Gross-Enzersdorf. This work was carried out within an on-going long term N-research project that has been in progress since 1990. It consisted of three levels of fertilizer and an unfertilized control, with two replicates (Fig. 4). Fertilizer was applied at 100% (equal to the amount of N expected in the grain, 120 kg ha^{-1}) 150% and 200% (Table II). Winter wheat was planted in the fall of 1995. To capture residual mineral N after harvest of 1996, a cover crop miture of mustard ('Maxi'), valley vervenia ('Angela') and buckwheat ('Bamby') was grown between August and November 1996. In 1997, soybean ('Nebraska,' maturity group 000) was planted followed by winter barley ('Montana'). The winter wheat had two fertilizer applications during spring and was irrigated once. Tillage details are provided in Table III.

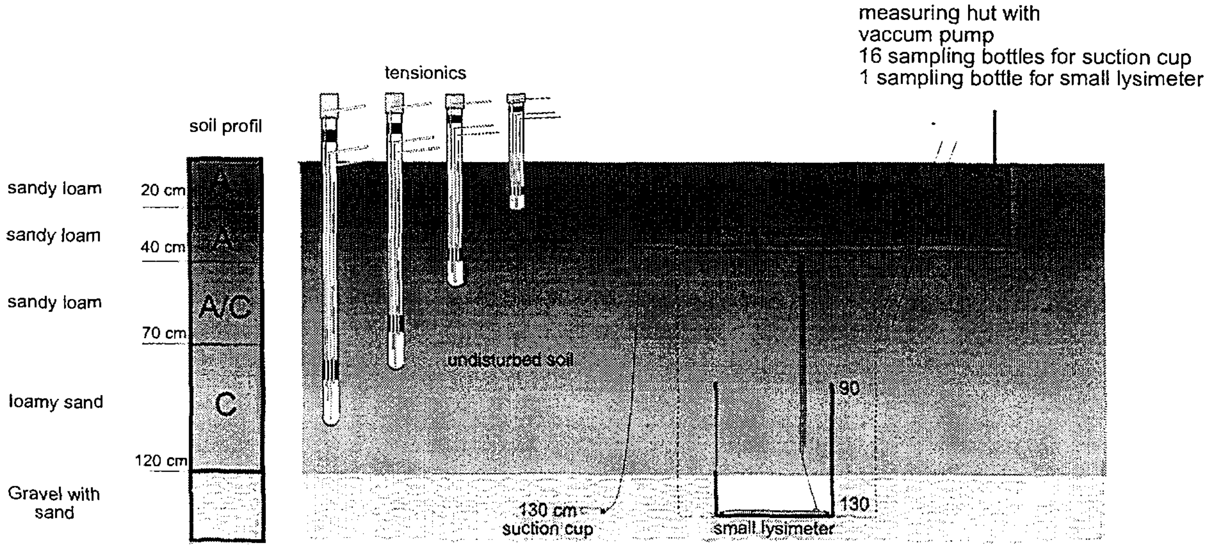

FIG. 5. Cross-section of the experimental site.

In the spring of 1996, ^{15}N-enriched (2.5% a.e.) fertilizer was applied to the winter wheat. In the subsequent years, unenriched fertilizers were applied. However, ^{15}N-enrichment determinations were made in 1996 for the cover crop, and in 1997 and 1998 for soybean and winter barley, respectively.

Figure 4 shows the location of the eight micro-plots (^{15}N-enriched fertilizer) and macro-plots (unenriched fertilizer). In addition, the figure shows the location of the neutron probe and gypsum blocks for measuring water content. Each micro-plot had four tensionics and two suction cups (Fig. 5). The lysimeter was installed in the plot fertilized at 150% (Fig. 4). Water samples from the sixteen suction cups and the lysimeter were collected weekly.

All water samples collected from the field were brought to the laboratory and nitrate concentrations measured spectrophotometrically. The soil-water samples were treated by the diffusion method [14] in preparation for $^{14}N/^{15}N$ ratio determinations with an on-line Carlo Erba automated Dumas-combustion system connected to a VG-SIRA mass spectrometer at the International Atomic Energy Agency's Laboratory in Seibersdorf, Austria.

3. RESULTS AND DISCUSSION

Large numbers of soil samples were collected from the study area and physical and chemical properties determined (Table IV). The soil was a typical czernosem, sandy loam to a depth of 70 cm and loamy sand from 70 cm to 120 cm. No gravel was present to 120 cm, but gravel and sand were present at greater depths. In the upper layers, the organic matter content was 2%. The pH for all depths was in the range from 7.0 to 7.5 and Ca content was about 25%..

TABLE IV. PHYSICAL AND CHEMICAL SOIL PARAMETERS

Soil depth (cm)	Sand 2000–50 μm	Silt 50–2 μm	Clay < 2 μm	Organic matter (Vol%)	Available water (Vol%)	kf-Value (m/d)
0–20	33.2	45.1	21.7	2.6	14.3	75
20–40	34.0	43.2	22.8	2.3	15.3	2
40–70	33.1	42.8	23.1	0.8	14.7	17
70–120	46.9	38.5	14.6	0.3	13.4	2

Water content was measured at several depths by neutron probe, gypsum blocks, and tensiometer, mostly on a weekly basis. Determinations made at 20, 50, 80 and 100 cm revealed that each device showed similar patterns (Fig. 6 a–d). After a rainstorm. the 20-cm data from the gypsum blocks and neutron probe showed predictable rising trends. At the 20th week, approximately, when no rainfall had been recorded during the preceding days, both devices showed rapid downward trends indicating drying of the soil and, accordingly, the tensiometer showed increases in suction. Similar observations were made for other depths. However, for unknown reasons, from approximately the 22nd week, the gypsum blocks showed a rising water content (Fig. 6c), in contrast with the neutron probe, which indicated declining moisture, and the tensiometer's increasing suction. Such differences may have been due to the measurement devices being located at slightly different depths, and soil variability may have played a role. Also, the profiles assayed were different: the data provided by the neutron-probe at 20 cm provided an average for 10 to 30 cm, whereas the gypsum block measured the water content at 20 cm. Furthermore, these measurements are indirect and need calibration.

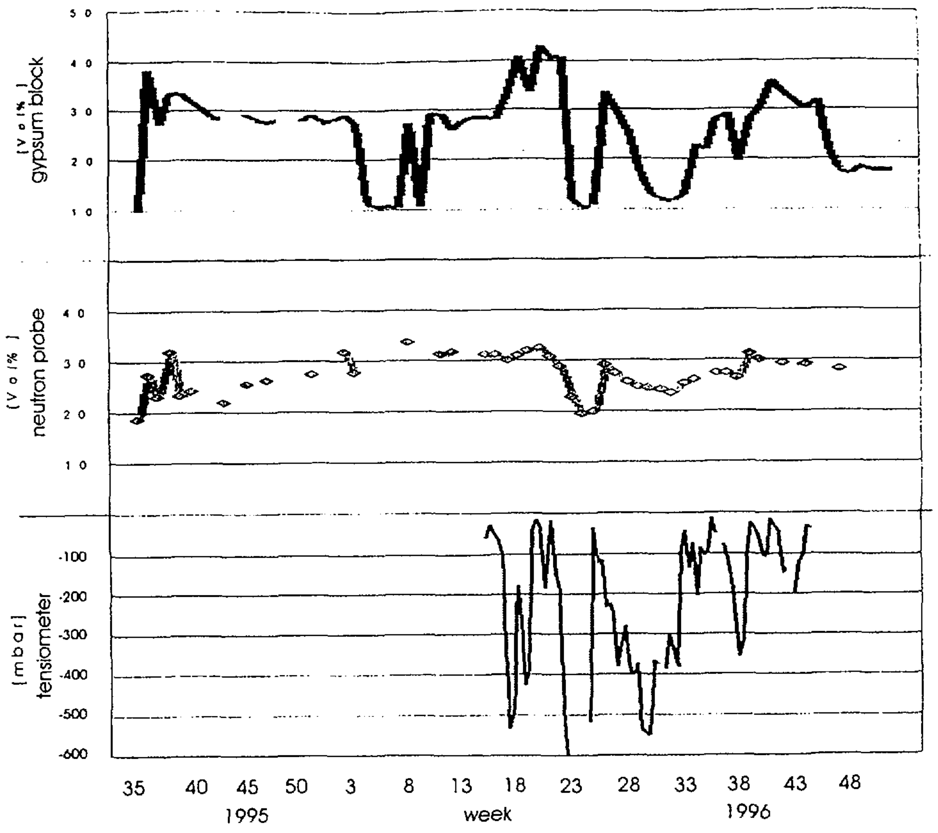

Fig. 6a. Water content and suction at 20 cm depths of soil profile.

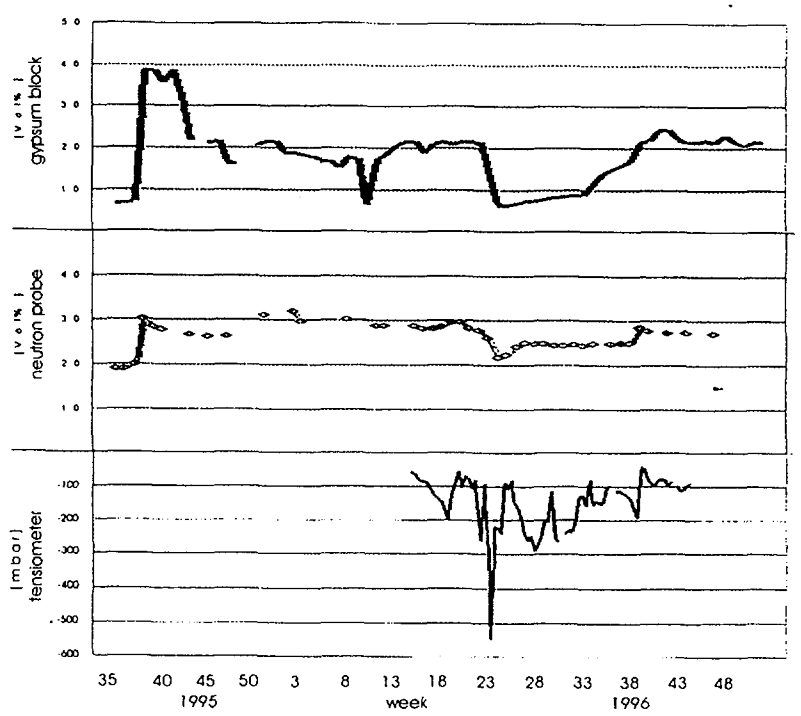

Fig. 6b. Water content and suction at 50 cm depths of soil profile.

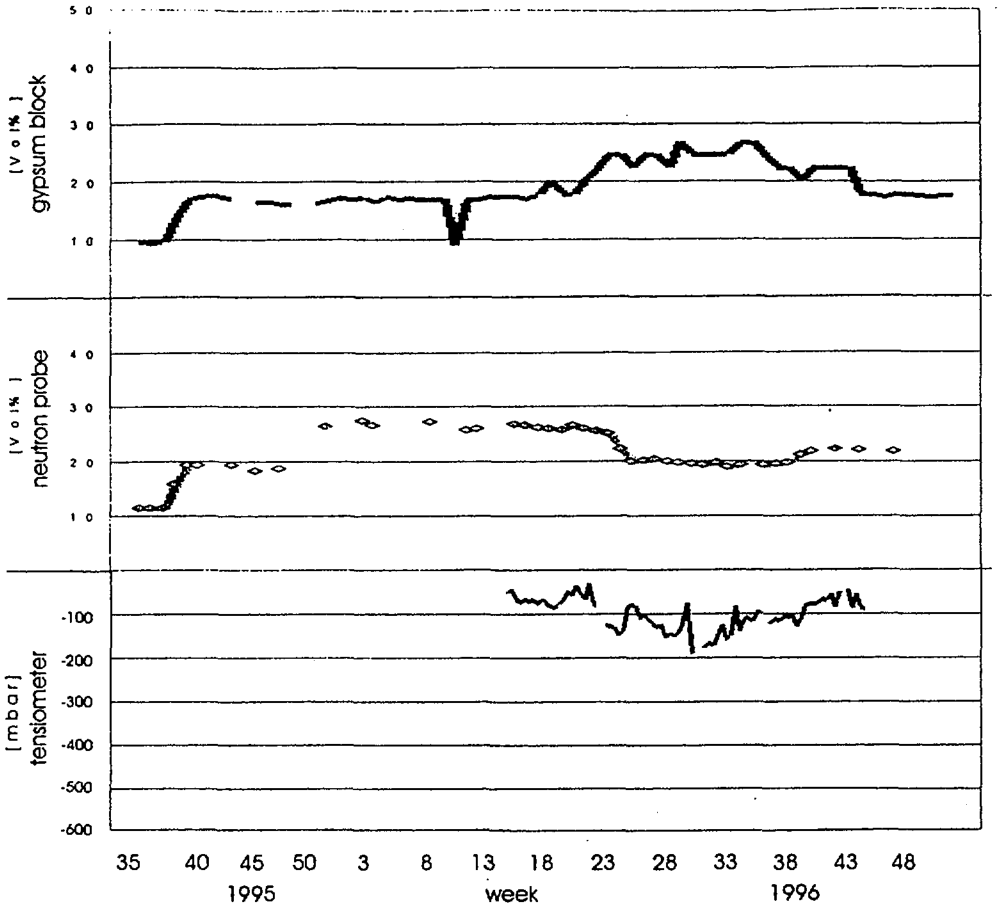

Fig. 6c. Water content and suction at 80 cm depths of soil profile.

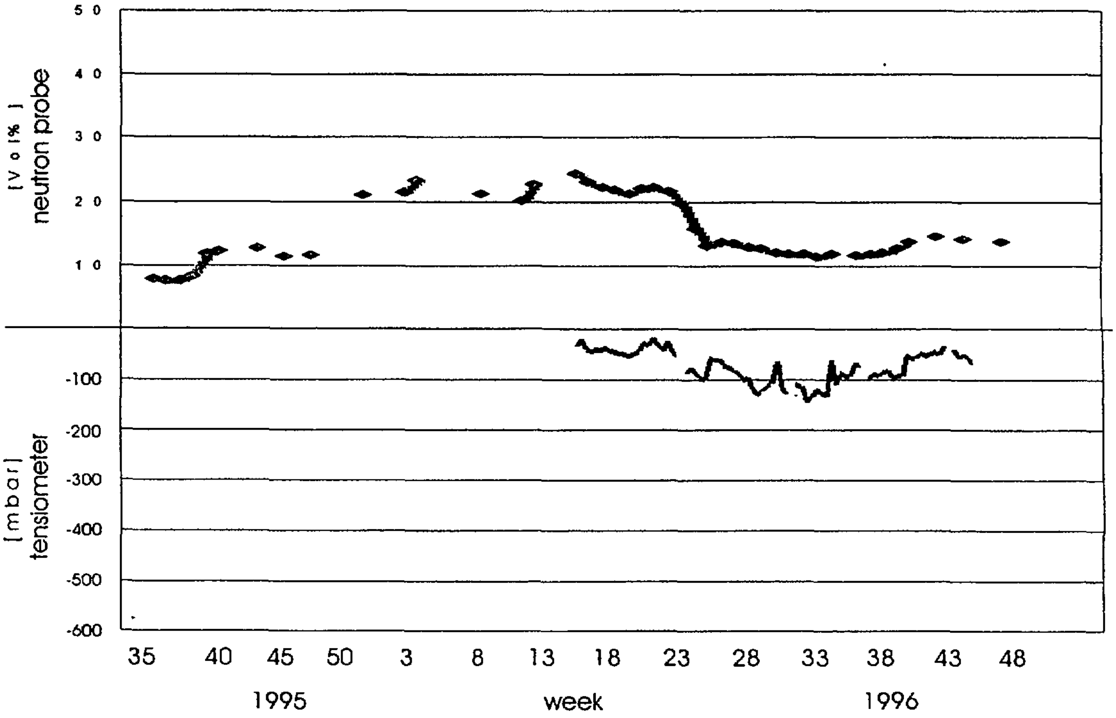

Fig. 6d. Water content and suction at 100 cm depths of soil profile.

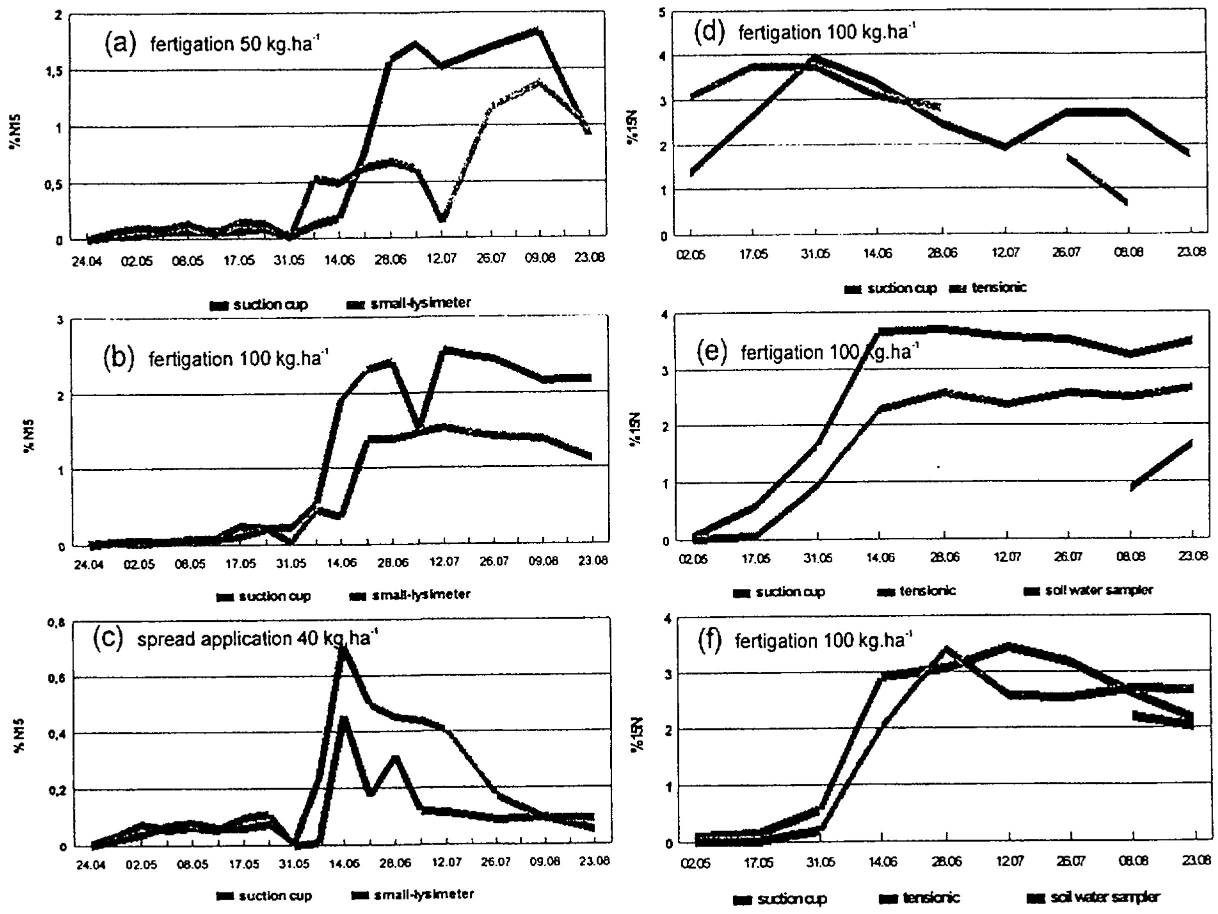

Fig. 7. Average ^{15}N-concentrations in soil water from different devices.

Figure 7 shows ^{15}N-enrichment data at different depths for samples collected by various devices installed in the apple orchard fertilized at different rates of N from mid-April to the end of August 1995. During the first 2 months, at 105 cm, ^{15}N-concentrations from the suction cups and lysimeters were similar (Fig. 7a–c). Subsequently, rapid increases in concentration were observed. Figure 7d–f shows the comparison of ^{15}N-concentration from suction cups, tensionics and soil-water samplers; clearly, all of the measuring devices were successful in assaying ^{15}N-concentration in the soil profile. The minor differences in the data may have been due to the flow through macro-pores or to within-plot variability of the soil.

Concerning N leaching in the orchard, the best results were obtained with broadcast application: the maximum ^{15}N-concentration at 105 cm depth was only 0.7% (Fig. 7c). The highest concentration that was obtained with 50 kg N ha^{-1} applied as fertigation was 1.7%, whereas 100 kg N ha^{-1} as fertigation produced a value of 2.5% for the same depth.

Rainfall on the study area was recorded at a local hydrology station, and percolation was measured with the lysimeters installed below the root zone. During the investigation period (September 1995 to December 1996), 860 mm of rainfall and 96 mm of percolation were recorded. In the spring, large amounts of moisture were present throughout the soil profile due to winter rainfall, shown by neutron-probe measurements at several depths (Fig. 6). The percolation started after the rainfall in week 8 of 1996, and continued to increase, largely due to rainfall during weeks 13 to 15. The large amounts of percolation during this period was partly due to low water requirements of the winter wheat. Rainfall in the subsequent weeks was diminished. At the same time, the water requirement of the crop was higher,

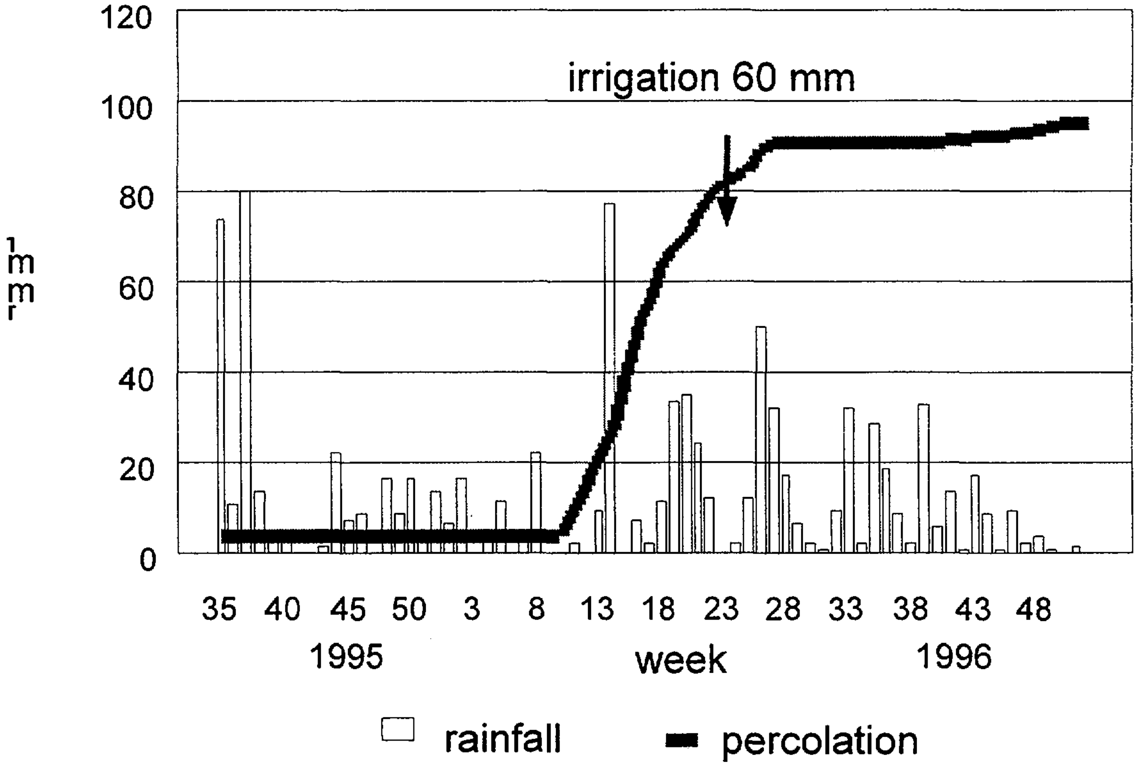

Fig. 8. Average rainfall and percolation measured using lysimeter.

therefore, 60 mm of irrigation was applied. This resulted in an increase in the water content of the soil profile to a depth of 50 cm, as shown by neutron-probe measurements (Fig. 6a, b). However, moisture deeper in the soil declined from week 15 onwards (Fig. 6c, d), indicating that all of the applied water was consumed by the crop.

All the devices used to measure ^{15}N-concentration gave similar results. Therefore, nitrate concentrations were measured at a depth of 130 cm using suction cups for the investigation of 1995–96, when winter wheat was grown followed by a cover crop. For each fertilizer application, four measurements were made (Fig. 4). Nitrate concentrations increased with the amount of fertilizer applied (Fig. 9). However, the weighted average nitrate concentration remained the same. The unfertilized plots had a nitrate concentration of 111 mg L^{-1}, slightly more than double the European Union guidelines for groundwater. In fertilized plots, the average nitrate concentration was 215 mg L^{-1} for 100% fertilization, 352 mg L^{-1} for 150% and 477 mg L^{-1} for 200%. The nitrate concentration in unfertilized plots also rose slightly after the 8th week of 1996, due to mineralization of soil organic matter.

The ^{15}N-concentrations of samples collected in suction cups ranged between 0.005% to 0.01% from a possible maximum of 2.5%. These low values showed that only a small part of the fertilizer applied during spring, for all treatments, percolated through the soil profile. For plots with 100% and 150% fertilizer treatments, only a few measurements of ^{15}N were possible as rainfall was light at the end of 1996 (Fig. 8). The total amount of fertilizer consumed by winter wheat and the cover crop ranged from 35 to 44% of total N-fertilizer applied (Table V), indicating that a significant amount of fertilizer remained in the soil that could leach with subsequent percolation.

The grain yields of winter wheat varied between 3.07 and 5.23 t ha^{-1}, depending on N applied (Table V). In the unfertilized plots, 21 and 63 kg N ha^{-1} were recovered in straw and grain, respectively. In the fertilized plots, 60 to 73 kg N ha^{-1} were found in the straw, and 111 to 116 kg N ha^{-1} in the grain. A 60-kg N ha^{-1} increase in the amount of fertilizer applied resulted in an increase of only 5 kg N ha^{-1} in

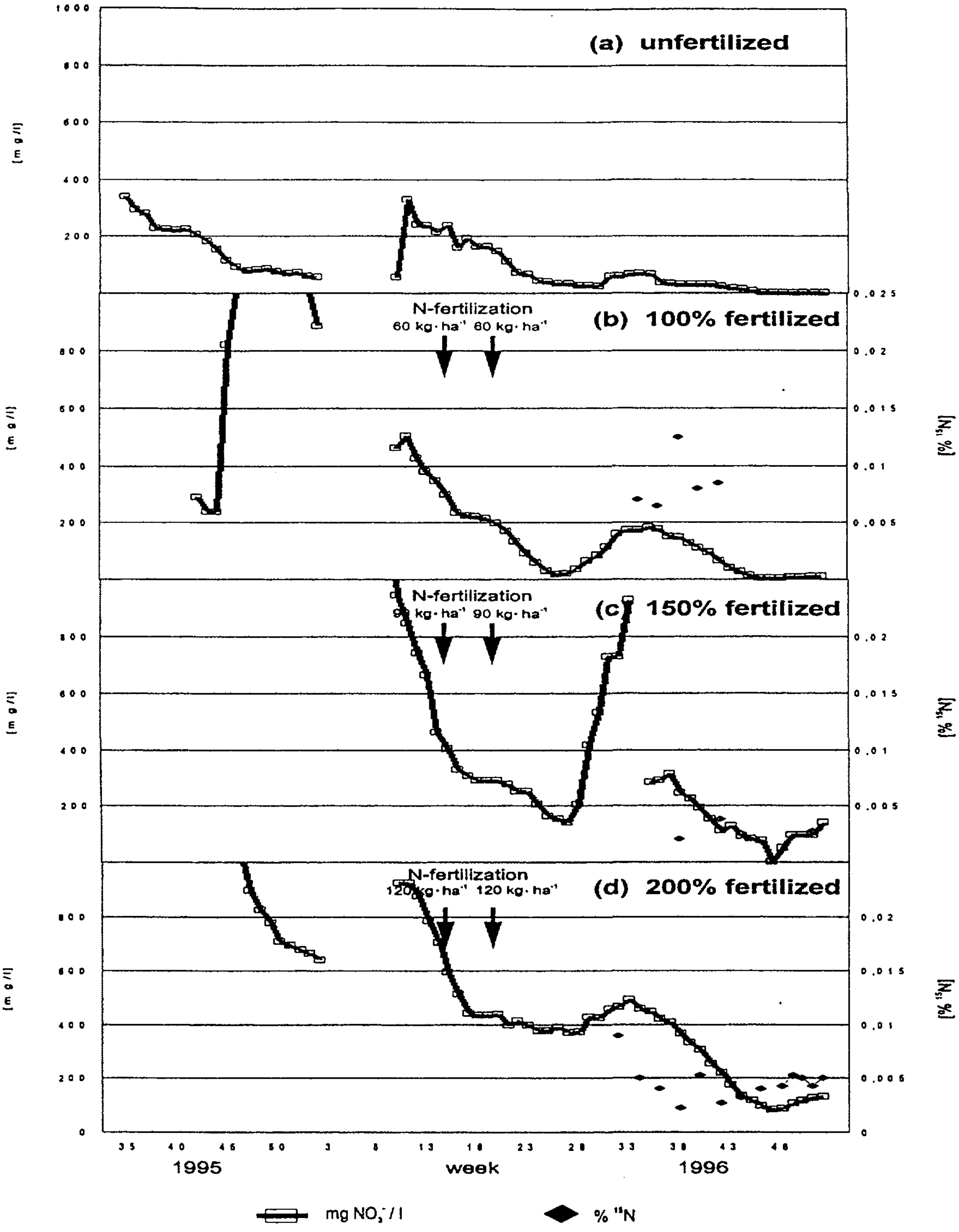

Fig. 9. Nitrate concentration below root zone of the soil for four doses of fertilizer application.

TABLE V. YIELD AND NITROGEN UPTAKE FROM SOIL AND FERTILIZER DURING 1996–1998

treatment		Yield [t.ha^{-1}]		Total N [kg.ha^{-1}]			fertilizer N [kg.ha^{-1}]			Total N / fertilizer N	Total fert. / fertilizer N*)
		straw	grain	straw	grain	Total	straw	grain	Total		
Winter Wheat 1995/96	0% N	5.75	3.07	21	63	84					
	100% N	8.52	5.23	62	111	172	19.4	30.7	50.1	29.1%	41.8%
	150% N	9.46	5.14	60	116	177	28.6	49.7	78.3	44.3%	43.5%
	200% N	9.18	5.12	73	113	187	37.2	41.3	78.6	42.1%	32.7%
Cover Crop 1996	0% N	1.19		25		25					
	100% N	1.94		51		51	0.7		0.7	1.4%	0.6%
	150% N	2.24		52		52	1.2		1.2	2.4%	0.7%
	200% N	3.53		118		118	2.9		2.9	2.4%	1.2%
Soybean 1997	0% N	3.98	1.46	15	60	75					
	100% N	5.68	2.15	22	98	120	2.1	1.6	3.7	3.1%	3.1%
	150% N	5.41	2.08	26	99	125	4.7	3.5	8.2	6.6%	4.5%
	200% N	5.57	2.02	36	102	138	6.6	5.6	12.2	8.8%	5.1%
Winter Barley 1997/98	0% N	4.83	2.08	16	27	43					
	100% N	9.61	5.09	41	99	140	1.3	0.7	2.0	1.5%	1.7%
	150% N	5.98	4.91	36	114	150	1.9	0.9	2.9	1.9%	1.6%
	200% N	12.20	5.81	79	128	208	3.4	1.5	5.0	2.4%	2.1%

*) depending on the nitrogen fertilization in 1996, 120 kg.ha^{-1} for 100%, 180 kg.ha^{-1} for 150%, 240 kg.ha^{-1} for 200%,

TABLE VI. TOTAL NITROGEN AND PART OF FERTILIZER IN SOIL IN kg.ha^{-1}

Depth/time	Total nitrogen in soil July 1996	Nitrogen from fertilizer in soil July 1996	Nitrogen from fertilizer in soil November 1996
Fertilization 100%			
0–30	5,850	19	15
30–60	3,670	7	7
60–90	2,193	5	4
Total	11,713	31	27
Fertilization 150%			
0–30	6,060	43	23
30–60	4,753	11	11
60–90	2,588	9	1
Total	13,400	62	35
Fertilization 200%			
0–30	6,280	32	31
30–60	4,870	16	11
60–90	2,345	4	9
Total	13,495	52	51

plant uptake. A further increment in fertilizer application to 240 kg N ha^{-1} increased plant uptake by only 15 kg N ha^{-1}, which explains the higher concentrations in Fig. 9; however, grain yield decreased.

The measured and calculated [15] values for crop uptake from fertilizer varied from 50 to 79 kg N ha^{-1}. Uptake from soil in unfertilized plots was 84 kg N ha^{-1}, and 122 kg N ha^{-1} from the fertilized plots. With the highest fertilizer rate (200%, 240 kg N ha^{-1}) only 33% of plant N was from fertilizer, whereas with 120 and 180 kg N ha^{-1}, the values were 42% to 44%. Also, through the use of the cover crop, a lot of N was captured for possible subsequent benefit to a grain crop, ranging from 25 kg N ha^{-1} on unfertilized plots to 118 kg N ha^{-1} with 200% fertilization, most of which came from the soil. The part from fertilizer was only 0.6% for 100% fertilization, 0.7% for 150% fertilization and 1.2% for 200% fertilization.

Subsequent crops, soybean and winter barley, were fertilized with unlabelled fertilizer (Table III). As with wheat, total-N values were greater for the higher rates of fertilizer. From the fertilizer applied to winter wheat in spring 1996, 3.7 to 12 kg N ha^{-1} were taken up by soybean. In 1998, the ^{15}N-fertilizer uptake by winter barley was 2.0 to 5.0 kg ha^{-1}, which represented 1.7 to 2.1% of the amount applied. The total fertilizer uptake by crops, in 1998, during vegetative growth ranged between 41% (99 kg N ha^{-1} for the 200% treatment) and 50% (91 kg N ha^{-1} for 150%). With the 100% treatment (120 kg N ha^{-1}) the total crop uptake was 57 N kg ha^{-1} , which was 47%.

Soil-N contents of 0.02% to 0.14% indicated approximately 12 to 13.5 t N ha^{-1} in the 90-cm root zone. Of this pool, 1 to 2% may be crop-available through mineralization. At the same time, part of the mineral N may be retransformed and immobilized. To determine what fraction of the organic N came from fertilizer, ^{15}N-analyses were made on soil samples collected from three soil depths. The samples were taken after the harvest of winter wheat and after the harvest of the cover crop. The amount of N from fertilizer decreased with depth (Table VI), indicating that only a small part of the applied fertilizer penetrated to deeper soil layers. Similar conclusions are also made for Fig. 9. In total, 27 to 65 kg N ha^{-1} N from fertilizer were immobilized in the soil, 22% to 36% of what had been applied. This amount may be used by other crops.

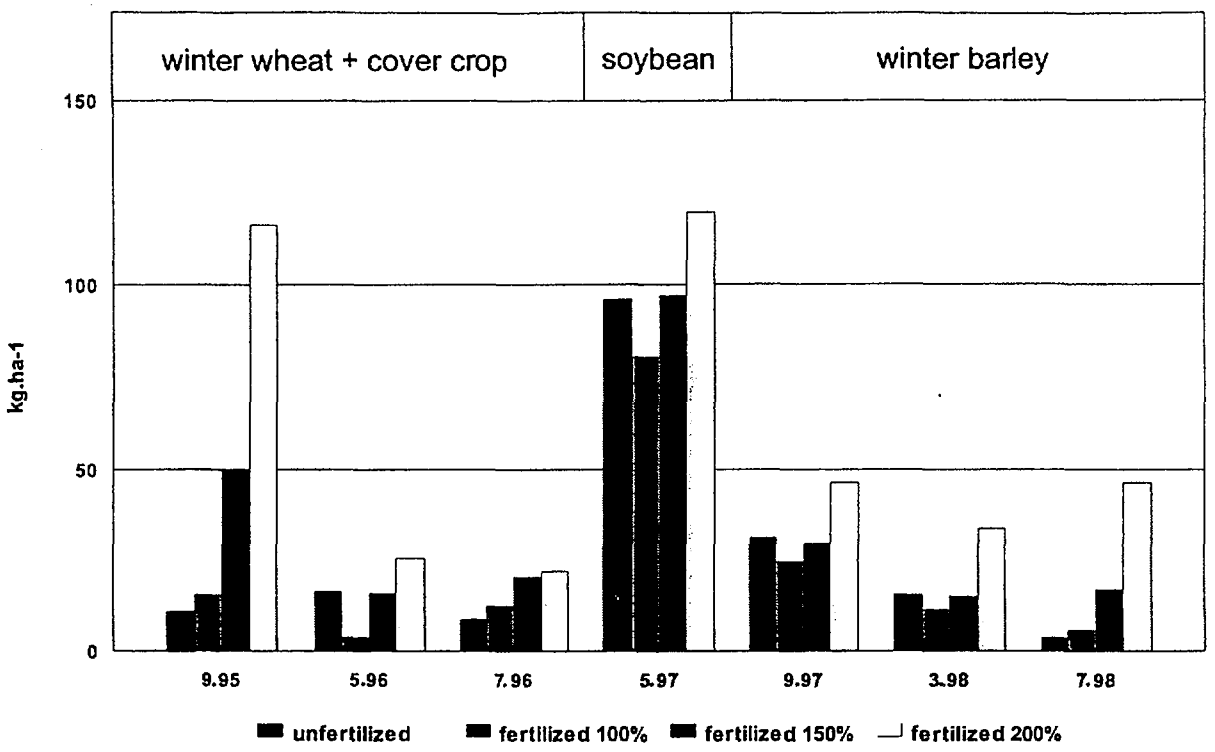

Fig. 10 Plant available nitrogen for the rooting depth of 90 cm.

The measurements of the plant-available N in the rooting depth gave the possibility of adjusting the N fertilization depending on the plant requirement. Using the N_{min}-method, actual plant-available N content in the soil was obtained on a given day, which was directly dependent on N-fertilization (Fig. 10). Due to the poor growth of plants in unfertilized plots and high mineralization rates, the plant available N was often higher than that derived from the soil in the 100% fertilized plots. The large amount of N in the unfertilized plots may lead to higher N leaching to groundwater.

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