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Seventy-Two Lysimeters for Measuring Water Flows and Nitrate Leaching under Arable Land

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Abstract: At the agricultural research station Agroscope in Zurich-Reckenholz (Switzerland), a large lysimeter facility was built in 2009. Totally 72 lysimeters, each with 1 m^2 surface area and a depth of 150 cm, were monolithically excavated at three agricultural sites differing in soil type. All lysimeters can be operated from a walkable basement. Twelve of the lysimeters are weighable and are instrumented with tensiometers, temperature sensors, suction cups and FDR probes in four depths (10, 30, 60, and 90 cm), each with two replicates. The other 60 lysimeters are non-weighable. Seepage water is measured by tipping counters. All lysimeters are used for agronomic experiments. The main focus is on water flows and nitrate leaching under different cropping systems, soil tillage intensities, fertilization regimes, and soil types. All treatments are replicated three times. The results of the first seven experimental years (2009-2015) show that water flows of the lysimeters are subject to large annual variations, depending on climatic conditions and crops grown. Annual seepage volumes fluctuated between 116 mm and 754 mm. Results on nitrate leaching are shown by the example of an experiment on the ploughing-in time of a cover crop. Ploughing up in spring led to reduced N leaching compared to ploughing up already in autumn. Tracer experiments with bromide show that the mass transport through the soil profile takes about 0.5 to 1.5 years. A large lysimeter facility has large advantages and offers many opportunities, but is also a challenge in terms of financial and human resources.

Key words: lysimeter, agriculture, nitrate leaching, water flows, seepage water, bromide

Introduction

Lysimeters are widely recognized instruments by science. On the one hand, results of lysimeter studies can be relevant for agricultural practice. On the other hand, they allow measuring and quantifying of the water and nutrient transport under controlled conditions. Thus, they are an interface between laboratory and field experiments. A large advantage of lysimeters consists in measuring loads of leached substances, and not only concentrations. The new technical possibilities of excavating undisturbed soil monoliths and the sensor technoloqy (precision weighing, installation of various probes) have made lysimeter research even more attractive. Accordingly, there are numerous recently built lysimeter facilities and many scientific publications from lysimeter studies (e. g. Hagenau et al. 2015, Hannes et al. 2015, Klammler and Fank 2014, Nolz et al. 2014, Schelle et al. 2013). Lanthaler and Fank (2005) and www.lysimeter.at provide an overview of existing lysimeter facilities in Europe.

Lysimeter research in Switzerland has a long tradition. In 1922 the first lysimeters were built (Geering 1943). In the early 1970s, several facilities with large lysimeters were constructed. However, some of these have been abandoned in the meantime, and only a few lysimeter facilities were built recently. Prasuhn et al. (2011) give an overview of the existing and abandoned lysimeter facilities in Switzerland. At the Agroscope site Zurich-Reckenholz, another lysimeter facility is currently operated besides the one in the focus of this paper. Built in 1980, it comprises twelve weighing lysimeters, each having a surface area of 3.14 m^2 and a depth of 2.5 m, and two types of disturbed soil (loamy Cambisol above moraine loam and sandy-loamy Cambisol above moraine gravel). In the year 2010, the facility was covered with a plastic tunnel to control water inputs to the lysimeters. Experiments on the influence of different irrigation regimes on nitrate leaching (Prasuhn and Vögeli Albisser 2014) and on the leaching of herbicides (Torrento et al. 2015) were carried out.

By building a large lysimeter facility in the years 2008-2009 at the Agroscope site Zurich-Reckenholz, it became possible to carry out targeted research in water and substance flows. The large number of 72 lysimeters allows to carry out numerous practically-relevant experiments simultaneously. With the twelve weighing lysimeter, which are additionally equipped with various types of probes, process research can be performed. The focus of our research is on nitrate leaching under agricultural crops. In Switzerland, 40 mg L^{-1} of nitrate is the limit for drinking water quality according to food legislation, but the “Water Protection Ordinance” requires less than 25 mg L^{-1} of nitrate for groundwater used or intended as drinking water. The measurements of the NAQUA National Groundwater Monitoring show that 40 mg L^{-1} of nitrate is exceeded in some monitoring sites and 25 mg L^{-1} in many sites of the Swiss midlands. Nitrate concentrations and loads are also elevated in some surface waters. The “Convention for the Protection of the Marine Environment of the North-East Atlantic” (OSPAR) has set up the target of reducing the nitrogen (N) load in flowing waters by 50% compared to 1985. This target has not yet been met for the Rhine at Basel at the border to France and Germany. The inputs from point sources (sewage treatment plants and stormwater overflow) have been greatly reduced in recent decades. The inputs from diffuse sources (mainly agriculture), therefore, gain in importance (Prasuhn and Sieber 2005) and practical measures to reduce nitrate leaching under agricultural land are required. Using lysimeters such mitigation measures can be tested and their efficiency can be shown.

As most of our lysimeter studies are long-term experiments, only a few results have already been published from the facility built in 2008-2009 (Prasuhn et al. 2015, Spiess et al. 2015). In the following, the lysimeter facility is described first. Then some selected results on water flows and substance transport are presented. More information can be found under www.lysimeter.ch.

Lysimeter Facility and Measurement Devices

The lysimeter facility of Agroscope Zurich-Reckenholz contains 72 lysimeters with a surface area of 1 m^2 and a depth of 1.50 m (Figure 1). The freely-draining gravitation lysimeters contain undisturbed soil up to a depth of 1.35 m. The deepest 15 cm are filled with purified quartz sand and gravel (three layers of 5 cm with particle size distribution: 0.10-0.50 mm; 0.71-1.25 mm; 3.15-5.60 mm) to enable free drainage. To obtain soil monoliths, the specially developed and internationally established method of Umwelt-Geräte-Technik GmbH (UGT) has been used (Meissner et al. 2004, 2008).

At the bottom of the lysimeters, the volume of seepage water is measured with tipping buckets having a volume of 100 ml. Seepage generation is interpolated to 5-minutes values between two tilting measurements. At each tilt 1.5 ml of water flows into a sample bottle, allowing flow-proportional sampling of small volumes. Water samples are analysed every 14 days for nitrate (NO_3), ammonium (NH_4), and other nutrients by segmented-flow injection analysis (sFIA). Climatic data are recorded by a national meteorological station of MeteoSwiss at a distance of 20 m from the lysimeter station.

Fig. 1. Lysimeter facility: above-ground part with temporary grassland, sugar beets and oilseed rape in the year 2011, and basement with the weighing lysimeters.

Twelve of the lysimeters are weighable and instrumented with different types of probes. Frequency domain reflectometry sensors (FDR; ThetaProbe ML2x, Delta-T Devices, Burwell, UK), equilibrium tensiometers (EQ15, Ecomatic, Munich, Germany), pressure transducer tensiometers (Tensio 150, UGT, Müncheberg, Germany), and temperature sensors are installed in two replications at soil depths of 10, 30, 60 and 90 cm. The measurement accuracy of the weighing load cells (UGT WM 100, UGT, Müncheberg, Germany) is indicated to be 10 g (or 0.01 mm of water). The temporal resolution of all sensors has been set to 5 min.

The weighing lysimeters stand on steel trusses. They can be lowered easily from the weighing position using a special lifting platform. So at any time technical inspection measures on the sensors and load cells can be carried out in the lysimeter basement with little effort and regardless of weather conditions. The non-weighing lysimeters stand on concrete pedestals. With three adjustable heavy-duty hinged feet the lysimeters can be adjusted (Fig. 2).

Detailed information about the lysimeter facility and the installed devices can be found in Prasuhn et al. (2009) and Sturzenegger (2010).

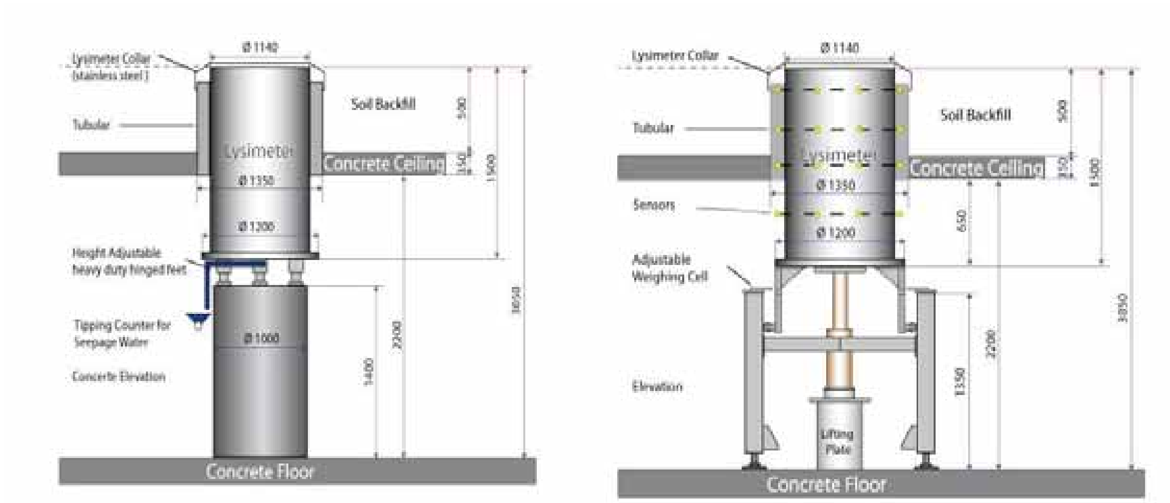


Fig. 2. Scheme of a weighing and a non-weighing lysimeter (length specifications in mm).

Location and Climatic Conditions

The lysimeter facility is located at Zurich-Reckenholz in central Switzerland at an altitude of 443 m above sea level (Fig. 3). Temperature averages 9.4 °C with a maximum of 19 °C in July and a minimum of 0.3 °C in January (Fig. 4). Mean annual rainfall is 1054 mm. Most rainfall occurs from May to August. During the winter months a part of the precipitation falls as snow. Annual fluctuations in precipitation can be large (Tab. 1). The years 2011 and 2015 were very dry with a rainfall deficit of 258 and 222 mm with respect to the long-term average; 2012, however, was relatively moist with an excess of 111 mm. Seepage volumes in the 72 lysimeters averaged 376 mm from 2009 to 2015 (Tab. 1). Seepage volumes and nitrate leaching are not only influenced by total annual rainfall but also by season. The main drainage period is during the winter months, since evapotranspiration is low then due to low temperatures. In the dry year of 2011, the seepage volume in a grass-cropped lysimeter was only as high as 141 mm, 74% less than in the wet year of 2012 with 537 mm. Differences in seepage volumes can even be greater depending on crops grown. In 2001 under sugar beets, seepage volume was only 116 mm, whereas in 2012 under silage maize it amounted to 754 mm.

Table 1. Annual precipitation and seepage volumes (average of 72 lysimeters, different crops and soils)

Year	2009	2010	2011	2012	2013	2014	2015
Precipitation (mm)	1018	1021	796	1165	1029	988	832
Seepage volume (mm)	260*	438	204	570	495	284	377

* only March – December

Fig. 3. Location of the lysimeter facility at Zurich-Reckenholz.

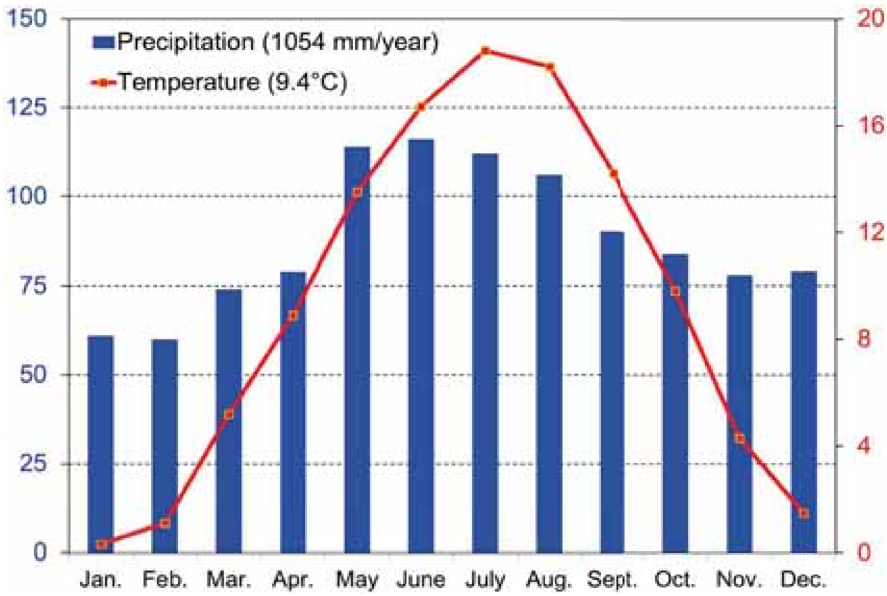


Fig. 4. Monthly precipitation and temperature at Zurich-Reckenholz (long-term mean of 1981-2010).

Soils

The lysimeters contain three different soils: 48 Cambisols from Grafenried (canton Berne), 12 pseudogleyed Cambisols from Zürich-Reckenholz (canton Zurich) and 12 Luvisol from Schafisheim (canton Aargau) (soil classification: WRB 2015), which have been used as arable land for many years. The three soil types are widespread in Switzerland. They do not differ greatly in texture, hydraulic conductivity and nutrient reserves. All soils are loams or sandy loams, profound and have a large water-storage capacity and nutrient supply. The three different soil profiles with the most important soil horizon characteristics are depicted in Figures 5, 6 and 7. The designation of the soil horizons corresponds to the Swiss terminology (Bodenkundliche Gesellschaft Schweiz, 2010).

Experiments

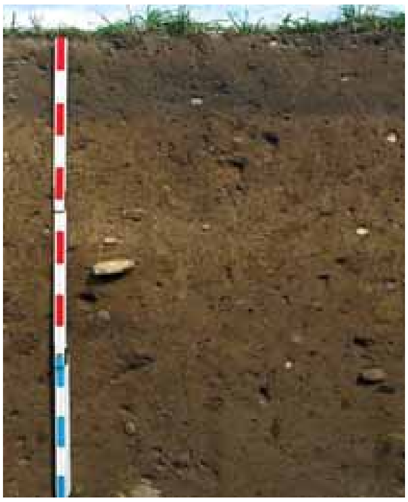
Between 2009 and 2015 three long-term experiments (tillage systems, N fertilization regimes, farming systems) and several two or three-year experiments (slurry application in winter, ploughing-in time of a cover crop, age of temporary grassland) were established (Tab. 2, Fig. 8). The experiments on tillage systems and farming systems were established on the three different soils in order to assess the influence of the soil type. All treatments are replicated three times to allow for a statistical analysis.

Farming practices (tillage, sowing, fertilization, plant protection, harvest) are performed by hand, following common practice in timing and methods. Before maturity most crops are protected against birds with a net. Crop yields and N removal with harvested products are recorded. The lysimeters are exposed to natural weather conditions and not irrigated.

The crop rotations of the experiments (Tab. 3) are typical for Swiss farms. To prevent longer fallow periods between the harvest date of a crop and the sowing date of the following crop, cover crops are established and used as green manure or for forage production. By now 15 important crops for Swiss agriculture were grown in one or several years: beetroot (*Beta vulgaris* L. ssp. *vulgaris* (Conditiva Group)), field peas (*Pisum sativum* L. convar. *sativum*), grain maize (*Zea mays* L.), oilseed rape (*Brassica napus* var. *napus* L.), spring barley (*Hordeum vulgare* L. ssp. *vulgare*), sugar beets (*Beta vulgaris* ssp. *vulgaris* var. *altissima* Döll), sunflower (*Helianthus annuus* L.), silage maize (*Zea mays* L.), spelt (*Triticum spelta* L.), spring wheat (*Triticum aestivum* L.), temporary grassland (white clover, *Trifolium repens* L.; red clover, *Trifolium pratense* L.; perennial rye-gras, *Lolium perenne* L.; orchardgras, *Dactylis glomerata* L.; meadow fescue, *Festuca pratensis* Huds.; timothy, *Phleum pratense* L.), winter triticale (*X Triticosecale* Wittm.), winter barley (*Hordeum vulgare* L. ssp. *vulgare*), winter rye (*Secale cereale* L.), and winter wheat (*Triticum aestivum* L.). Potatoes and most vegetables are difficult to grow on the lysimeters due to the small surface of 1 m^2.

Table 2. Experiments established on the lysimeter facility between 2009 and 2015

Experiment	Trials and management
Tillage systems	Influence of two tillage systems (mouldboard ploughing and mulch seeding) on three soils
Fertilization regimes	Influence of N fertilizer application rate (0%, 70%, 100%, 130% of N of official recommendations, CULTAN (ammonium fertilizer is injected into the soil), (Sommer 2000)
Farming systems	a) Comparison of organic agriculture with integrated production on three soils b) Extensive organic agriculture
Slurry application in winter	Influence of slurry application in winter on grassland
Ploughing-in time of a cover crop	Influence of the ploughing-in time of a cover crop (November versus March)
Age of temporary grassland	Influence of the age of temporary grassland at ploughing-in time (one versus three-year temporary grassland, autumn versus spring)



Ahp: 0–25 cm; sandy loam: (16% clay / 32% silt / 52% sand) **Soil organic matter (SOM)**: 1,7% **bulk density (BD)**: 1,45; **pore volume (PV)**: 45%
Bcn: 25–65 cm; sandy loam: (19% clay / 26% silt / 55% sand); **SOM**: 0,3%; **BD**: 1,56; **PV**: 42%
B(g)(t): 65–110 cm: sandy loam: (18% clay / 25% silt / 57% sand) **SOM**: 0,2%; **BD**: 1,60; **PV**: 41%
Bg(t): 110–150 cm sandy loam: (17% clay / 24% silt / 59% sand) **SOM:** 0,1%

Fig. 5. Soil profile of Grafenried (sandy-loamy Cambisol above ground moraine).

Ahp: 0–27 cm sandy loam: (17% clay / 28% silt / 55% sand) **Soil organic matter (SOM):** 2,0% **bulk density (BD)**: 1,50; **pore volume (PV)**: 43%
BE: 27–60 cm loam: (22% clay / 31% silt / 47% sand) **SOM**: 0,7%; **BD**: 1,53; **PV**: 43%
Bit: 60–85 cm loam: (26% clay / 19% silt / 55% sand) **SOM:** 0,6%; **BD**: 1,47; **PV**: 45%
It, cn: 85–110/125 cm loam: (28% clay / 23% silt / 49% sand) **SOM**: 0,4%
BC/C: 110/125–150 cm loam: (24% clay / 21% silt / 55% sand)

Fig. 6. Soil profile of Schafisheim (loamy Luvisol above gravel).

Ahp: 0–25 cm loam: (24% clay / 49% silt / 27% sand) **Soil organic matter (SOM)**: 2,5%; **bulk density (BD)**: 1,36; **pore volume (PV)**: 48%
Abcn: 25–32 cm silt loam: (23% clay / 53% silt / 24% sand); **SOM**: 1,9%
Bcn(g)(x): 32–65 cm clay loam: (31% clay / 49% silt / 20% sand) **SOM**: 0,7%; **BD**: 1,44; **PV**: 47%
Bg: 65–85 cm clay loam: (33% clay / 46% silt / 21% sand); **SOM**: 0,6%; **BD**: 1,39; **PV**: 49%
BCg: 85–105/135 cm silt loam: (19% clay / 61% silt / 20% sand); **SOM**: 0,2% **BD:** 1,61; **PV:** 41%
Cg: 105/135–150 cm silt loam: (18% clay / 65% silt / 17% sand)

Fig. 7. Soil profile of Zurich-Reckenholz (loamy-silty pseudogleyed Cambisol above ground moraine).

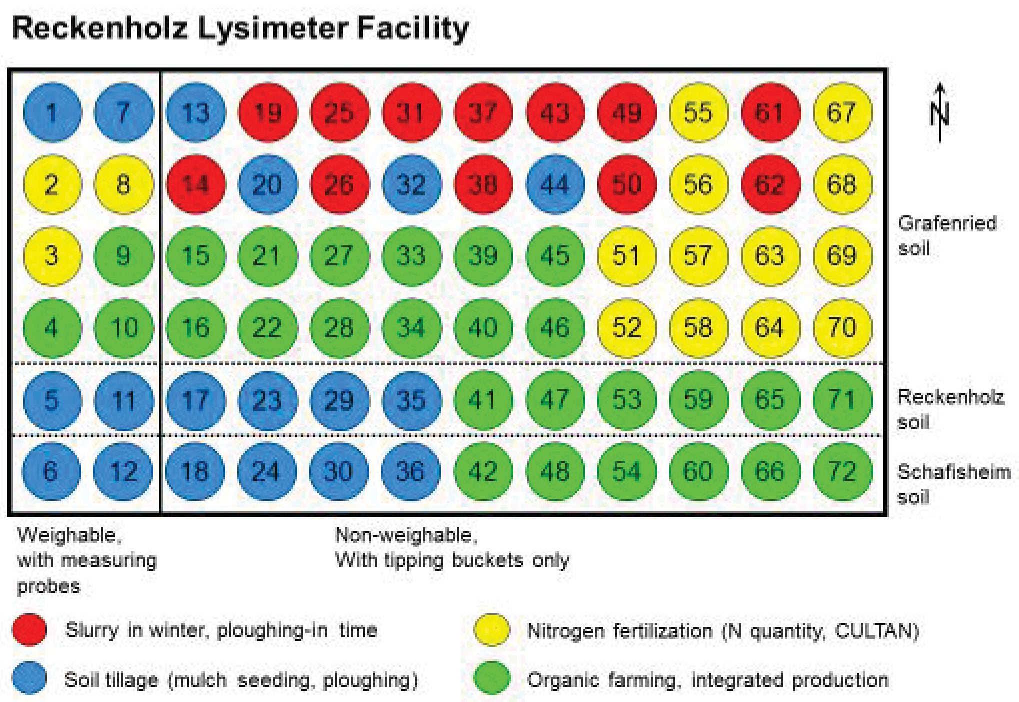


Fig. 8. Experimental design on the lysimeter facility 2009 - 2015.

Table 3. Experiments and crop rotations on the 72 lysimeters (BR = Beetroot, CC = Cover crop, FP = Field peas, GM = Grain maize, Ra = Oilseed rape, SB = Spring barley, Su = Sugar beets, SF = Sunflower, SM = Silage maize, Sp = Spelt, SW = Spring wheat, TG = Temporary grassland, TGS = Sowing year of temporary grassland, WT = Winter triticale, WB = Winter barley, WR = Winter rye, WW = Winter wheat)

Experiment	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Tillage systems	GM	WW+CC	FP	Ra	WB+CC	Su	GM
N fertilization regimes	SM	WB+CC	Su	WW	Ra	WT+CC	SM
Farming systems (1)	TG2	WW	Ra+CC	SM+CC2	BR	WB+TGS	TG1
Farming systems (2)	SM+CC	BR	WB+TGS	TG1	TG2	WW	Ra+CC
Organic extensive	TG1	Sp+CC	FP	Ra+TGS	TG1	SM	WW+TGS
various[1)]	TG1	TG2	TG3	SM	WR	WW	SF
various [1)]	SW+CC	SB+TGS	TG1	WW	WR	WB	SF

[1)] Slurry application in winter; Ploughing-in time of a cover crop; Age and ploughing-in time of temporary grassland; Winter wheat versus winter barley

Selected Results for Water Flows

Temporal Change in Weight over Seven Years under Different Crop Rotations

A gain in lysimeter weight reflects precipitation and weight loss means evapotranspiration and/or formation of seepage water. A change in weight of 1 kg at a surface area of 1 m^2 corresponds to 1 mm of water. The temporal change in weight clearly reflects the influence of climatic conditions and crops grown in the different years (Fig. 9). Seasonal rainfall distribution and water consumption by the crops grown are decisive for the time course and the magnitude of loss in weight. Large differences occur especially in summer. In winter, the soil is replenished with water in all lysimeters and usually water-saturated.

Under grain maize (lysimeter 1), silage maize (lysimeter 2), and temporary grassland (lysimeter 4), the dry year of 2015 gave rise to the greatest weight loss observed in the study period. But under winter wheat (lysimeter 10) weight loss was substantially lower. 2011 was also a dry year, but only weight loss under oilseed rape (lysimeter 4) was high, whereas lower decreases were observed under field peas (lysimeters 1 and 10) and sugar beets (lysimeter 2). The year of 2012 was the wettest to date, but in this year weight loss in lysimeter 10 reached its maximum under oilseed rape. In the different lysimeters, the maximum weight loss in summer was around 250 mm. In 2015 grain and silage maize suffered somewhat from drought stress. This is also reflected by the calculated crop coefficients for evapotranspiration, which were lower than in other years (Oberholzer 2016).

The measurements of soil water content by FDR probes clearly reflect the weight loss of the lysimeters, as shown by the data from lysimeter 9 in Figure 10 as an example. The readily plant available water was completely absorbed up to 90 cm depth only in 2011 (oilseed rape) and 2015 (temporary grassland). In other years enough soil water was always available to the crops already at depths above 90 cm.

Comparison of Two Crops in the Same Year

The two lysimeters shown in Figure 11 contain the same soil and are subject to the same climatic conditions, but show significant differences in evapotranspiration and seepage volume due to the contrasting development of the two crops under cultivation. Oilseed rape (lysimeter 9) is growing very fast in April, evapotranspiration increases strongly and the soil dries out. By the end of June, when oilseed rape was harvested, the weight of lysimeter 9 decreased by 250 kg and evapotranspiration was as high as 420 mm. Sugar beets (lysimeter 2) were sown only in mid-March and grew rather slowly. At the harvest time of oilseed rape, the lysimeter with sugar beets lost only 35 kg and evapotranspiration amounted to 260 mm. But the growth period continued until harvest in October. In early August, evapotranspiration of lysimeter 2 exceeded that of lysimeter 9 with temporary grassland sown after oilseed rape and by the end of the year, evapotranspiration in sugar beets was 175 mm higher than in the crop sequence oilseed rape - temporary grassland. Accordingly, the formation of seepage water under lysimeter 9 already started in mid-October and was 90 mm higher than in lysimeter 2 at the end of the year, where it only started in mid-December.

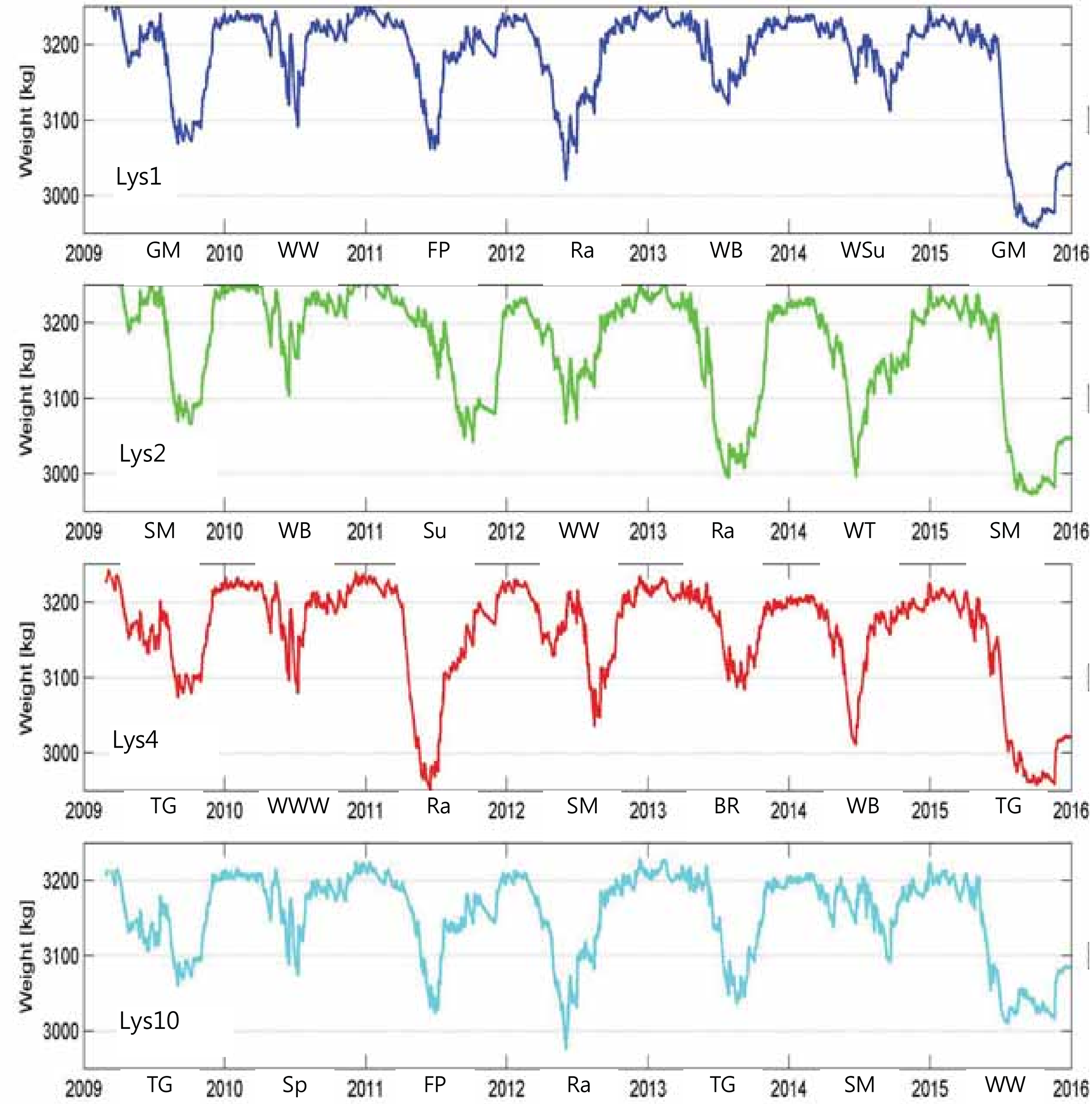


Fig. 9. Change in weight over 7 years under four lysimeters (Lys1, Lys2, Lys4, Lys10) with the same soil but different crop rotations. Abbreviations of crops see Table 3.

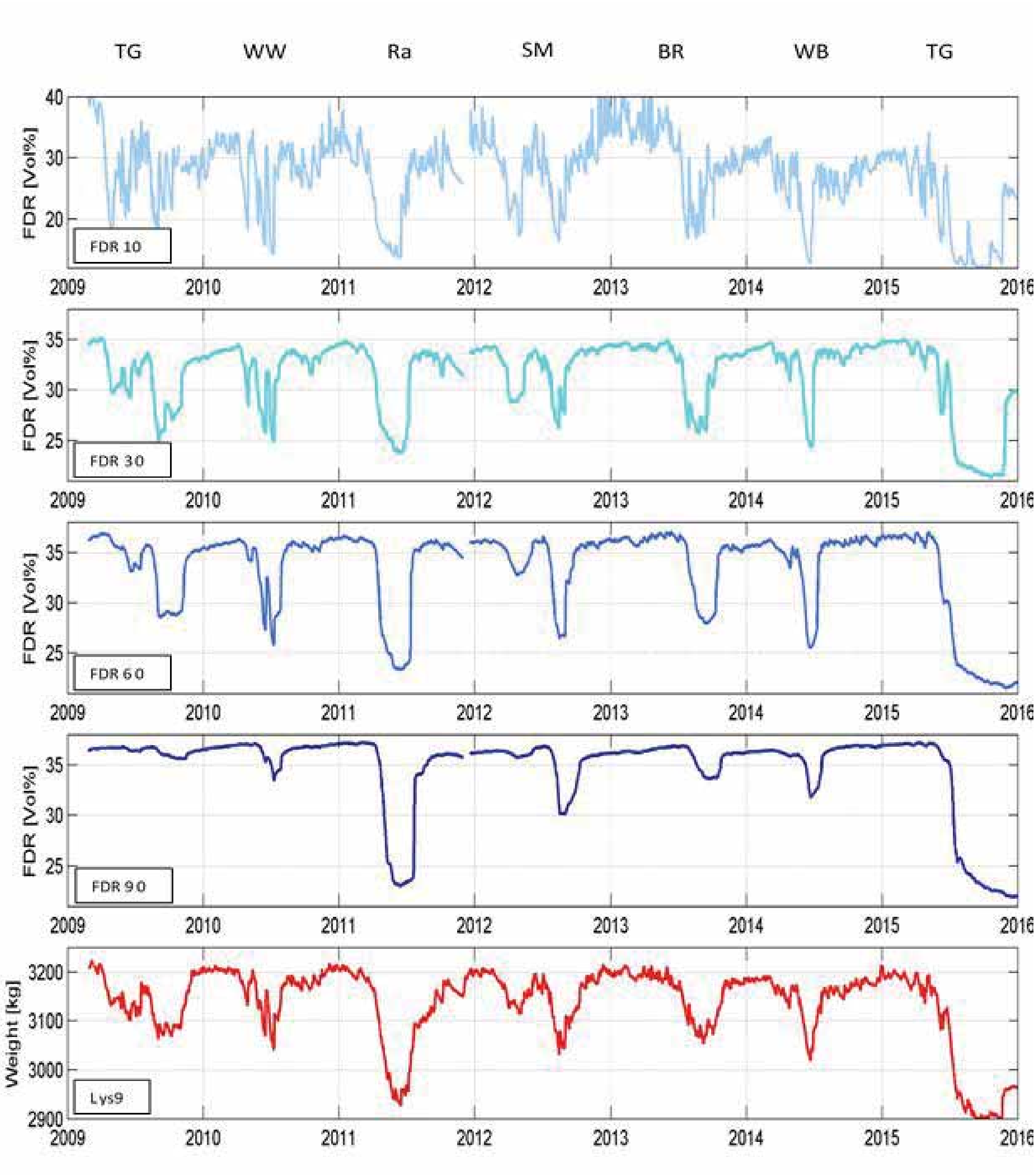


Fig. 10. Change in soil water content over 7 years in four soil depths measured by FDR probes and change in weight in lysimeter 9. Abbreviations of crops see Table 3.

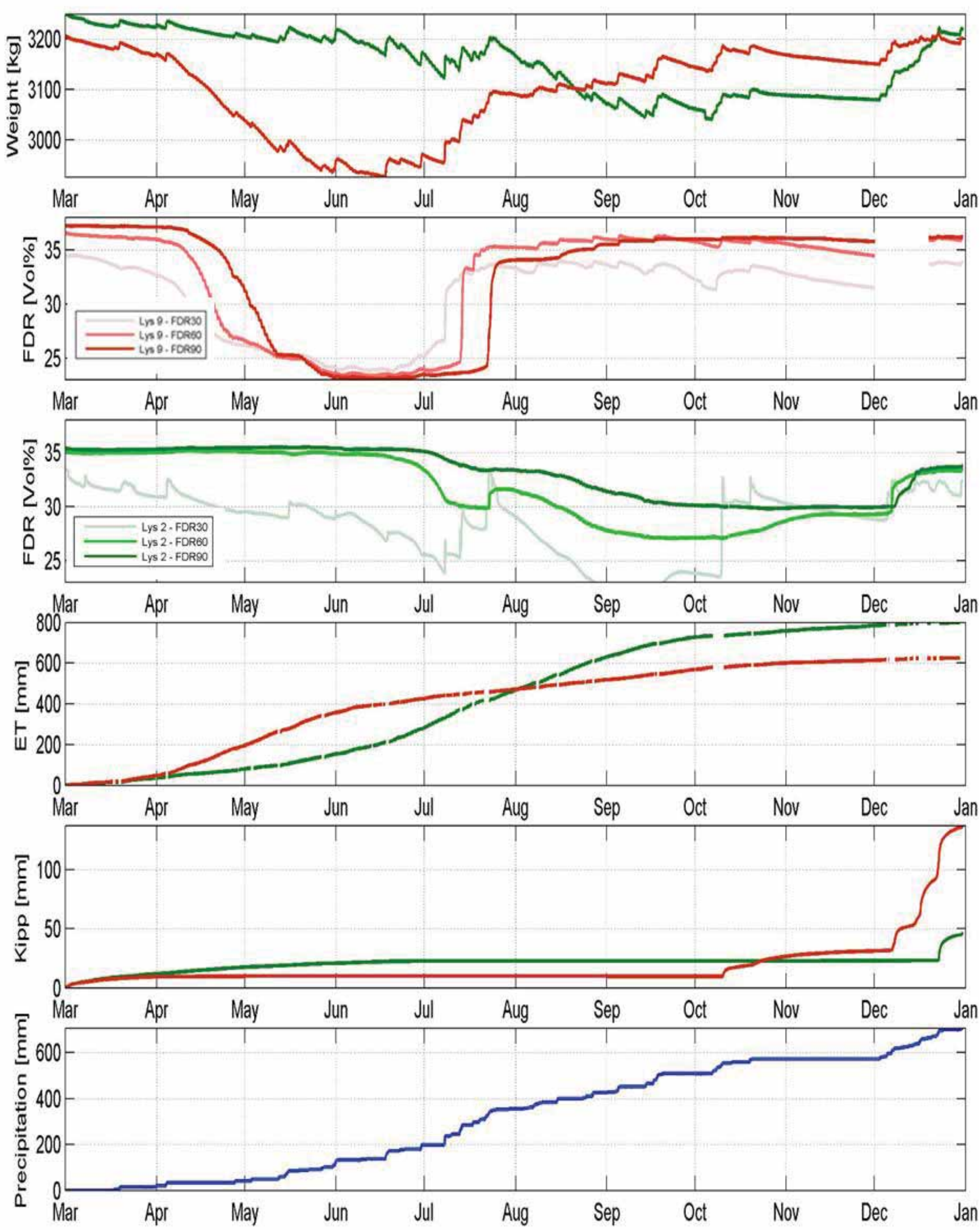


Fig. 11. Lysimeter weight, soil water content at 30, 60 and 90 cm depths (FDR), actual evapotranspiration (ET), seepage volume (Kipp) and precipitation for lysimeter 2 with sugar beets (green lines) and lysimeter 9 with oilseed rape (red lines) for the period March 1, 2011 to December 31, 2011.

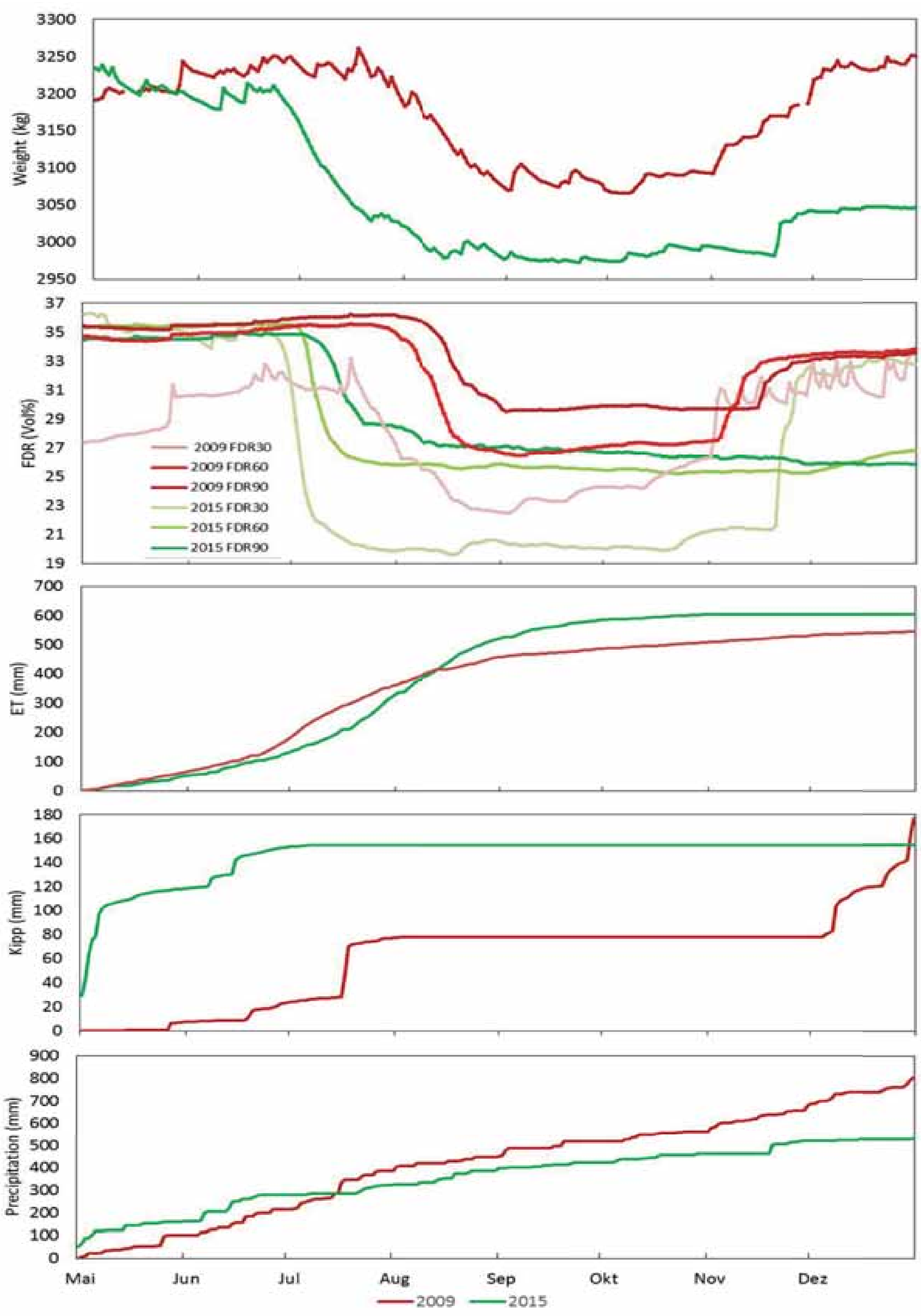


Fig. 12. Lysimeter weight, soil water content at 30, 60 and 90 cm depths (FDR), actual evapotranspiration (ET), seepage volume (Kipp) and precipitation for lysimeter 2 with silage maize for the periods May 1, 2009 to December 31, 2009 (red lines), and May 1, 2015 to December 31, 2015 (green lines).

Comparison of the Same Crop in Two Different Years

In the years 2009 and 2015, silage maize was grown on the same lysimeters. This allows a comparison of the same crop under different climatic conditions (Fig. 12). Total rainfall between May and December was in 2009 270 mm higher than in 2015 and seasonal distribution differed very much. In 2009 a heavy rainfall event in mid-July gave rise to a short period with seepage water, but overwinter drainage only started in early December. The data from lysimeter weight and soil water content clearly reflected this pattern. In 2015, however, rainfall in May and June was above average and resulted in a large seepage volume of 150 mm. The following summer and autumn were very dry. Soil water content decreased substantially in early July and remained at a low level at 60 and 90 cm depths. Therefore, no seepage water was produced by the end of the year.

In 2009 soil water content at 60 and 90 cm depths declined even one month later than in 2015 and at 90 cm depth the soil did not dry out as much. In early November replenishment of the soil profile started again. In 2015 evapotranspiration exceeded rainfall and the water deficit led to a dried-out soil until the end of the year. In 2009, however, rainfall was about 200 mm higher than evapotranspiration, and as a result the soil was water-saturated towards the end of the year and seepage water occurred.

Examples of a Detailed Analysis of High-Precision Weighing Data

High-precision weighing lysimeters are able to capture the water fluxes at the interface of soil, vegetation, and atmosphere (Unold and Fank 2008). The high weighing accuracy permits high-temporal-resolution measurements of precipitation including dew, fog, and rime (Meissner et al. 2007) for the calculation of actual evapotranspiration. We have also carried out studies on the formation of dew. Dew is formed when the air temperature is below the dew point. Temporal trend of dew point and air temperature at 5 cm above ground were taken from the data of the meteorological station and compared with the time course of the lysimeter weight (Fig. 13). In one night the dew point was from 22:40 to 6:30 below the air temperature (Boulos 2016). Exactly in this period, an increase in lysimeter weight took place although no rain fell. The quantity of dew depends on the duration of dew formation and the height of vegetation. Values for dew formation between 0.1 mm (temporary grassland) and 0.4 mm (silage maize) per night were found.

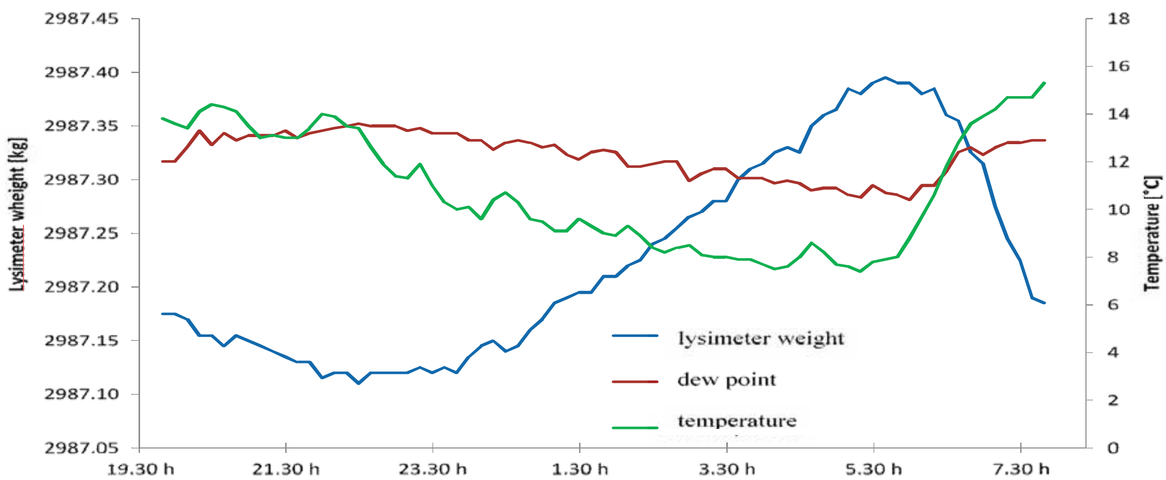


Fig. 13. Lysimeter weight, dew point and air temperature (10-min resolution) for the night of August 20 to 21, 2015 at lysimeter 1 with silage maize.

Wind or other disturbances can affect lysimeter weight (Nolz et al. 2013). To eliminate such artefacts from the data, accurate data-processing tools using filtering and smoothing algorithms were developed (Gebler et al. 2015, Hannes et al. 2015, Peters et al. 2014, Schrader et al. 2013). We have tested the "Adaptive Window and Adaptive Threshold" (AWAT) filter by Peters et al. (2014). Initial results show that the filter is very applicable to our data and that it is able to determine rainfall and evapotranspiration. However, the filter settings have to be adjusted separately for each lysimeter and each crop (Oberholzer 2016). Furthermore water use efficiency and crop coefficient of evapotranspiration were calculated for different crops (Oberholzer 2016). The results show that on the whole current water supply is sufficient under Swiss conditions. However, if drought events such as in 2015 become more frequent and even more intense, yield potential of typical Swiss arable crops will be limited by water availability.

Nitrate Leaching under Cover Crops: The Influence of the Ploughing-in Time

The establishment of cover crops between two main crops is an efficient measure for reducing nitrate leaching during the winter months. In 2009 an experiment on the impact of ploughing-in time on nitrate leaching was set up on six lysimeters (Spiess et al. 2015). The crop sequence comprised summer wheat as main crop and a hybrid of Chinese cabbage and turnip rape (*Brassica chinensis x Brassica rapa*) as cover crop in 2009, and spring barley followed by seeding temporary grassland in 2010. On three lysimeters, the winter-hardy cover crop was ploughed-in on November 20, 2009 (treatment 'Nov. ') and on the other three on March 19, 2010 (treatment 'March'). N fertilizer was applied as ammonium nitrate (120 kg N ha^{-1} in three split applications to wheat, and 60 kg N ha^{-1} in one dose to barley). The cover crop was not fertilized.

Seepage volume only accounted for one third of the rainfall, averaged over two years. This low value is due to below-average rainfall. No significant differences in seepage volume could be detected between the two treatments. In both treatments nitrate concentration of seepage water was always less than 3 mg NO_3 L^{-1} in the pre-period (Fig. 14). But immediately after the start of seepage water formation in December 2009, a sharp increase was observed in the treatment with ploughing up in November, but nitrate concentration never exceeded the Swiss tolerance value for drinking water of 40 mg NO_3 L^{-1}. In May 2010, nitrate concentration also increased after ploughing up in March and in autumn; it reached the same level as in the other treatment for a few weeks. In winter 2010/11, however, the treatment with ploughing-in in November showed again significantly higher concentrations. In both treatments, the tolerance value for drinking water clearly exceeded during this period.

While very little nitrogen was leached in the first year of investigation in both treatments, nitrate leaching in the second year was in the same order of magnitude as under other lysimeter with arable crops (Tab. 4). In winter 2009/10 as well as in the subsequent year the amount of nitrate leached was higher after ploughing-in in November than in March. For this reason it is recommended to plough down cover crops only shortly before sowing the succeeding main crop.

Table 4. Rainfall and seepage water, nitrate concentration of the seepage water and amount of nitrate leaching in the two treatments 'November' and 'March' (mean of 3 replicates)

Period	Precipitation (mm)	Seepage volume (mm)		Nitrate concentration (mg NO_3 L^{-1})		Amount of N leached (kg N ha^{-1})	
		Nov.	March	Nov.	March	Nov.	March
01.04.09 - 30.11.09	694	19	18	1.0	1.0	0.0	0.0
01.12.09 - 31.03.10	253	231	246	9.1	0.7	4.8	0.4
01.04.10 - 31.03.11	986	432	426	50.9	38.4	49.6	37.0

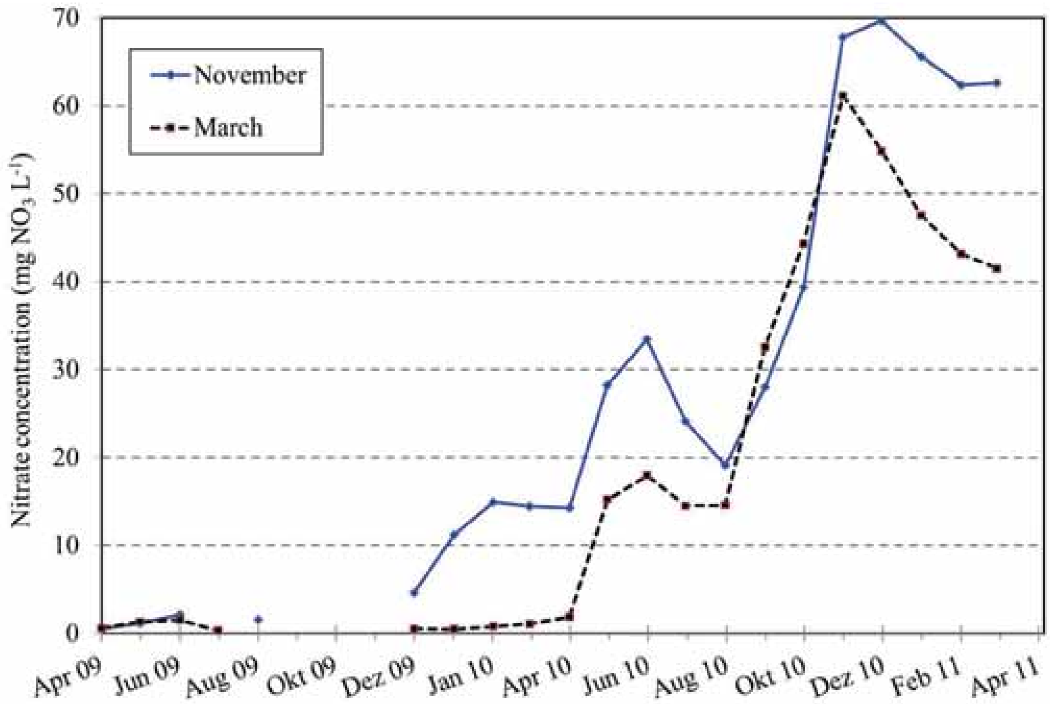


Fig. 14. Nitrate concentration of the leachate in the two treatments 'November' and 'March'.

Tracer Experiments with Bromide

Two experiments were carried out to study the transport of soluble substances in the soil in more detail. In the first experiment, performed on lysimeters of all the three soil types, a bromide tracer was applied on November 12, 2009, to a winter wheat crop sown on October 31, 2009. After harvest of wheat in summer 2010, straw was returned to the lysimeters, incorporated into the soil and a cover crop (Phacelia) was sown followed by field peas in 2011. In the second experiment, only on the Grafenried soil, bromide was applied together with nitrogen fertilizer on May 5, 2011, to sugar beets sown on March 22, 2011. After harvest of sugar beets, beet tops were incorporated into the soil and winter wheat was sown.

Bromide was applied as sodium bromide in a dose of 50 g m^{-2} (= 38.8 g Br m^{-2}) dissolved in one litre of deionized water. It was applied evenly on the soil surface with a hand sprayer equipped with drift protection. Flow-proportional composite samples from seepage water and samples from the suction cups of each depth were taken every 14 days and analyzed by ion chromatography (IC).

Plant samples were also taken in order to determine the Br uptake by plants, and were analysed after extraction by IC. Br uptake by plants differed greatly depending on crop, part of the plant (grains, straw, leaves, tubers), yield, season and weather conditions. The highest concentrations were found in sugar beet tops (> 30 g Br kg^{-1} dry matter). In wheat straw concentrations ranged from 4 to 7 g Br kg^{-1} dry matter. Both sugar beet tops and wheat straw were not removed from the lysimeters, but incorporated into the soil, so that the bromide contained in these plant parts - around 30% or 10% of the amount applied - can be released again. Stubble and roots remained in the soil and also contained bromide that was yet not analysed. The amounts of bromide in plant parts removed from the lysimeters were low. In the first experiment, 1% of the amount applied was removed in wheat grains in 2009 and 1% in field peas in the following year. In the second experiment, 3-4% were removed in sugar beets in 2011 and 1% by wheat grains in the following year (Prasuhn et al. 2015).

Figure 15 shows the curve of Br concentration in different soil depths for the first experiment on the soil of Grafenried. The translocation of bromide in the two other soils followed a similar pattern, but not so pronounced (not shown here). In 10-cm soil depth, extremely high Br concentrations above 500 mg L^{-1} were measured 20 days after Br application. However, this peak flattened very quickly again. In 30-cm depth, Br peaks were found two to four weeks later with values ranging from 348 to 412 mg L^{-1}. It took another two to six weeks until the peak reached 60 cm depth with concentrations varying between 167 and 258 mg L^{-1}. In 90-cm depth, maximum concentrations ranging from 151-184 mg L^{-1} were detected with another delay of ten to fourteen weeks. Peak concentrations declined with increasing soil depths, and curves of concentrations flattened. In 150-cm soil depth, at the bottom of the lysimeters, hardly any peak could be detected. In the first months of experimentation, Br concentrations were partially higher in 150-cm than 90-cm depth, a clear indication of the heterogeneity of the soil and the occurrence of macropore flow. The measurements by suction cups predominantly captured matrix flow. In other locations of the soil profile, however, bromide was translocated by preferential flow directly into the seepage water of the lysimeter.

From August to October 2010, a second, but smaller concentration peak of Br could be observed in all lysimeters in the 10, 30 and 60-cm soil depths. On August 3, 2010, harvested wheat straw was returned to the lysimeters and on August 23, 2010, it was incorporated into the soil and the cover crop of phacelia was sown. In the following weeks, bromide from straw, stubbles and roots was mineralized and released. Over winter Br concentrations were very low, but rose again in February/March due to the incorporation of phacelia, and tillage before sowing field peas on March 15, 2011. A third small peak was observed at 10 and 30-cm depths in September 2011. After the incorporation of pea residues on August 29, 2011, bromide from the crop residues was released.

In the second tracer experiment of 2011, a high Br concentration was measured at 10-cm soil depth immediately after tracer application (Fig. 16). In the following weeks, no seepage water occurred due to low rainfall. In the water samples of late July, only low Br concentrations were measured. After another period without seepage water, bromide could be detected at 30-cm depth in mid-October and it peaked in mid-November. At 60-cm depth, bromide first was measured in early November, and the peak occurred in late December. At 90-cm depth, bromide was only detected at the end of December, and just at the same time it occurred in the seepage water at 150-cm depth.

In the experiment of 2009, Br breakthrough appeared 34 days after tracer application. In this period, soil water content was already elevated, some rainfall events occurred and evapotranspiration was low. In the 2011 experiment, Br breakthrough happened only after 236 days. Sugar beets absorbed a lot of water in summer, thus preventing formation of seepage water until the end of December. The seepage volume required until the first detection of bromide ranged from 5 to 46 mm; it was similar in both experiments.

The total rate of bromide recovery in seepage water varied between 69% and 80% in the first experiment and 13% and 14% in the second (Fig. 17). In the latter experiment, a longer period with low rainfall followed the bromide application in May 2011. Sugar beets absorbed much bromide in water uptake. This bromide was released in large part only after the incorporation of the sugar beet tops in late autumn. Even after two years with 680 and 800 mm of seepage volume, only 14% of the bromide were leached out. Accordingly, a large part of the bromide must still be present in the soil in more or less immobile form. Bromide could have been diffused into micropores, where it is released only very slowly. Furthermore, it may be adsorbed to soil particles (e.g. iron or manganese) or incorporated into microorganisms or organic matter.

In the first experiment of 2009, the recovery rate of bromide varied according to soil type, ranging from 69% in the pseudogleyed Cambisol and 73% in the Luvisol to 80% in the Cambisol from Grafenried. In the latter soil, translocation of bromide was also fastest. 25% of the bromide was already leached out after three months and 40% after six months (Fig. 17). Accordingly, bromide plant uptake was lowest in the Cambisol.

On the whole the two experiments show that the recovery rate of bromide is lower in soils with more clay and increases more slowly. This supports the hypothesis that bromide is prevented for a long time by diffusion into smaller pores. If a long period with low rainfall and high evapotranspiration rates follows tracer application, a low recovery rate of bromide in seepage water can be expected. Bromide translocation through the soil profile was relatively slow in all soil types investigated and it took six to eighteen months or a seepage volume of 300 to 600 mm until the recovery of most of the tracer leached. The mean seepage volume at Zurich-Reckenholz is about 400 mm per year.

Results from the tracer studies let us suggest that translocation of nitrate occurs relatively slowly under climatic condition at the site. If not taken up by plants, immobilised by microorganisms or lost by denitrification, nitrate from mineralization of soil organic matter or from fertilizer applied takes 0.5 to 1.5 years for leaching out from the rooting zone of the soil.

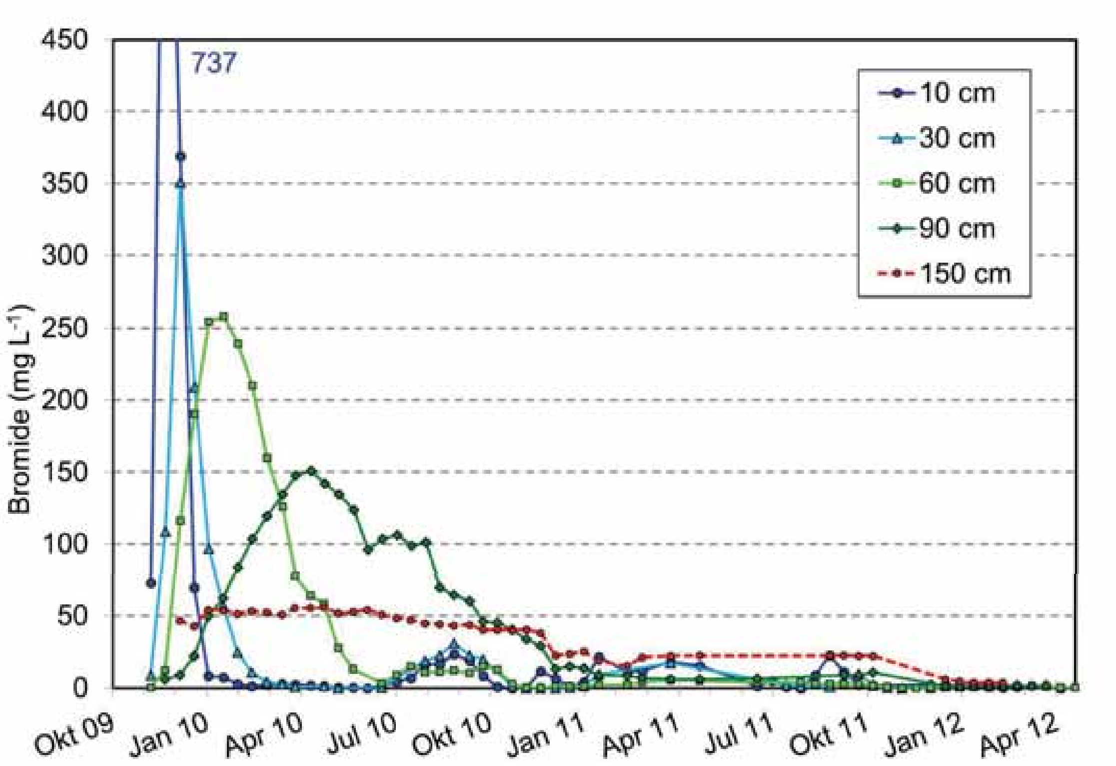


Fig. 15. Concentration of bromide at different soil depths in the tracer experiment started in autumn 2009 on the soil of Grafenried.

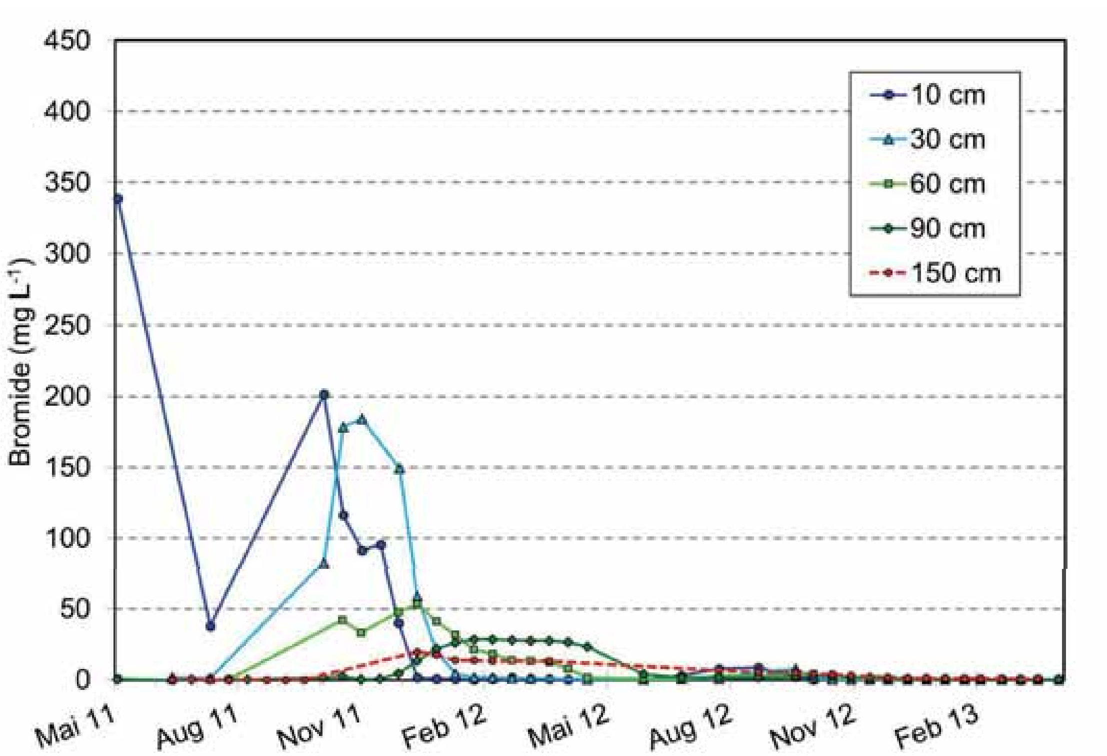


Fig. 16. Concentration of bromide at different soil depths in the tracer experiment started in spring 2011 on the soil of Grafenried.

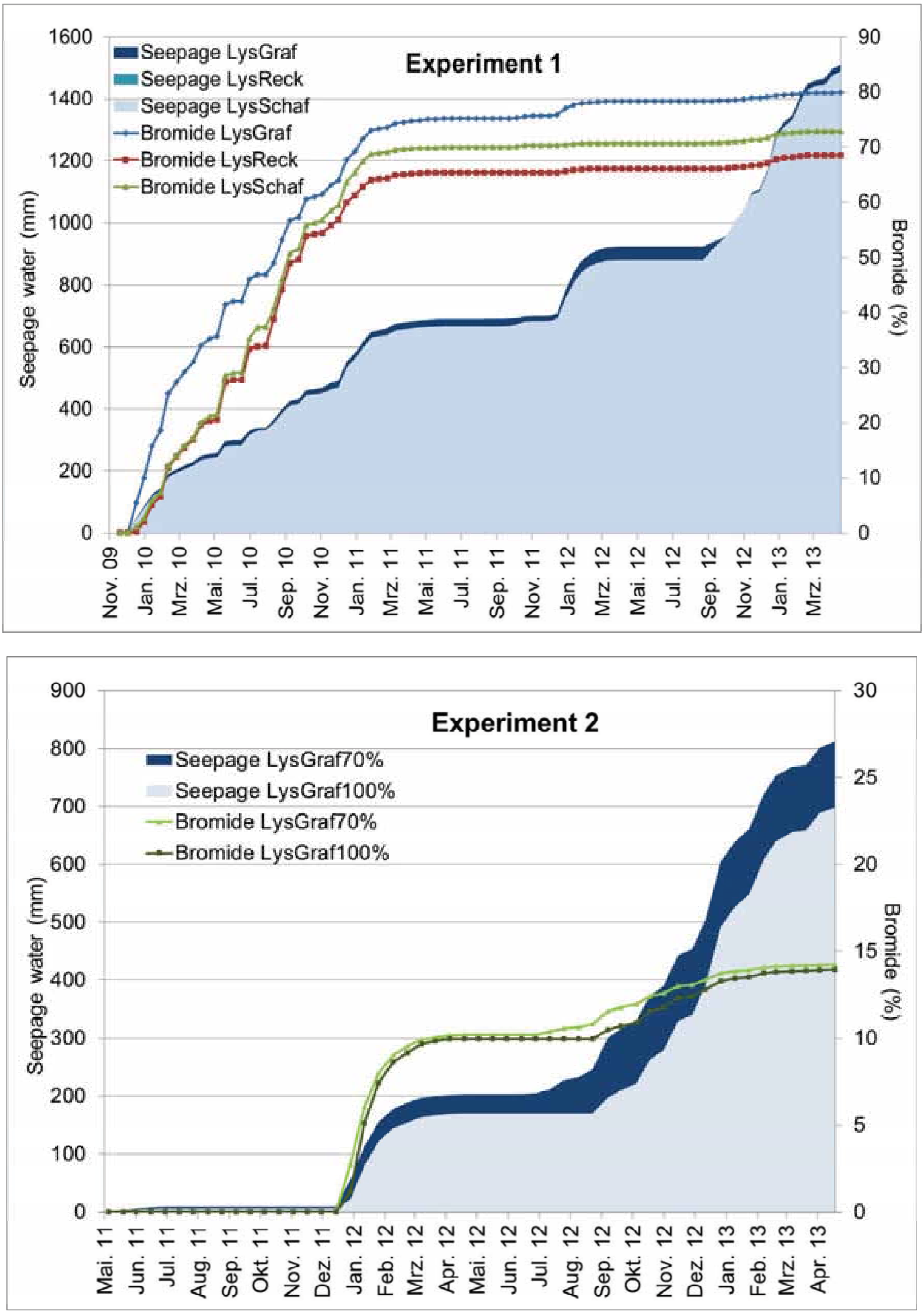


Fig. 17. Cumulative load of bromide leached in percent of the amount of bromide applied and cumulative seepage volume since bromide application for the two tracer experiments.

Conclusions and Outlook

The large number of lysimeters in the lysimeter facility of Agroscope allows for extensive experimental designs and evaluations. Assuming three replicates per treatment, 16 different treatments can be compared simultaneously on the soil of Grafenried and four treatments on the lysimeters of all three soil types. As the focus of our work is on practical recommendations regarding the effectiveness of measures to reduce nitrate leaching under arable land, multi-year experiments with crop rotations are necessary to get reliable results. This is the only way to account for the varying weather conditions and carry-over effects from preceding and/or cover crops. This also allows for comparison of farming systems such as organic farming and integrated production.

In addition, high-precision weighing lysimeters and measuring probes generate data giving better insight into processes of water translocation. They also can be used for modelling. Detailed water balances and the determination of crop coefficients of evapotranspiration and water use efficiency of different crops are possible. Tracer experiments provide additional insights into the translocation of solutes in soils. However, the amount of data produced in such a large number of lysimeters is huge. Its processing is extremely time consuming. In order to achieve results relevant to agricultural practice, careful management of lysimeters is very important. This also takes up a lot of time and requires careful planning. As a result of oasis effects we partly observed too high yields. These gave rise to increased N uptake by crops, elevated evapotranspiration, too low seepage volumes and, finally, also to reduced amounts of nitrate leached. Measures such as additional lateral shading of the lysimeter crops are currently being tested.

A large lysimeter facility has many advantages and offers many opportunities, but is also becoming a challenge in terms of agricultural management, servicing and maintenance, and thus financial and human resources.

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