

Indirect nitrogen losses of managed soils contributing to greenhouse emissions of agricultural areas in Austria: results from lysimeter studies

Alexander Eder · Günter Blöschl · Franz Feichtinger · Markus Herndl · Gernot Klammler · Johannes Hösch · Eva Erhart · Peter Strauss

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Abstract A considerable share of greenhouse gas emissions, especially N_2O , is caused by agriculture, part of which can be attributed to indirect soil emissions via leaching and runoff. Countries have to report their annual emissions, which are usually calculated by using the default value of 0.3 for $Frac_{LEACH}$, a factor that represents the fraction of nitrogen losses compared to total nitrogen inputs and sources. In our study we used 22 lysimeters, covering a wide range of soils, climatic conditions and management practices in Austria, to evaluate nitrogen losses through leaching and to calculate $Frac_{LEACH}$. The terms of the nitrogen mass balance of the lysimeters were directly measured for several years. Both grassland and arable land plots gave significantly smaller values of $Frac_{LEACH}$ than the default value. For grassland, $Frac_{LEACH}$ values of only 0.02 were found which varied very little over the entire observation

period. For arable sites, $Frac_{LEACH}$ values were higher (around 0.25) and showed significant variability between years due to variations in crop rotation, fertilization rates, and yields.

Keywords Nitrogen leaching · Lysimeter · IPCC · Agricultural emissions

Introduction

As part of the second commitment period of the Kyoto protocol, 37 countries have agreed to legally binding reductions in their greenhouse gas emissions. To be able to evaluate the progress in achieving the emission reduction goal, annual national inventory reports must be compiled and submitted to the United Nations

A. Eder (✉) · F. Feichtinger · P. Strauss
Institute for Land and Water Management Research,
Federal Agency for Water Management, Pollnbergstraße
1, 3252 Petzenkirchen, Austria
e-mail: alexander.eder@baw.at

G. Blöschl
Institute of Hydraulic Engineering and Water Resources
Management, Vienna University of Technology,
Karlsplatz 13/222, 1040 Vienna, Austria

M. Herndl
Agricultural Research and Education Centre Raumberg-
Gumpenstein, Raumberg 38, 8952 Irdning, Austria

G. Klammler
Institute for Water, Energy and Sustainability, Joanneum
Research Graz, Elisabethstraße 18/II, 8010 Graz, Austria

J. Hösch
Institute for Soil, Health and Plant Nutrition, Austrian
Agency for Health and Food Safety, Spargelfeldstraße
191, 1226 Vienna, Austria

E. Erhart
Bioscience Austria, Esslinger Hauptstrasse 132–134,
1220 Vienna, Austria

Framework Convention on Climate Change (UNFCCC). The Intergovernmental Panel on Climate Change (IPCC), which was set up by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP), established guidelines which provide internationally agreed methodologies intended for use by countries to calculate greenhouse gas inventories to report to the UNFCCC (IPCC 2006).

One of the listed greenhouse gases is nitrous oxide, N_2O , which has a global warming potential 296 times higher than carbon dioxide over a 100 year time scale. In Austria, the main sources of nitrous oxide emissions are agriculture, forestry and other land uses with a share of 59 % in the national total nitrous oxide emissions, although these sectors contribute only 9.1 % to the total Austrian greenhouse gas emissions (Environment Agency Austria 2013). 3.69 Gg N_2O were considered indirect soil emissions via nitrogen leaching, based on the Austrian National Inventory (Environment Agency Austria 2013). In Austria, manure, mineral fertilizer and plant residues are applied to soils, supplying nitrogen as a nutrient for plants. Depending on the environmental conditions, some of the nitrogen is leached as nitrate, nitrite or ammonia. These nitrogen losses can be calculated as a fraction of all nitrogen added to or mineralized in soils, a parameter that is termed $Frac_{LEACH}$. A part of the lost nitrogen is transformed to N_2O .

Mosier et al. (1998) suggested a value of 0.3 for $Frac_{LEACH}$, which is the value recommended in the IPCC Guidelines (IPCC 2000, 2006) as a default value. It was largely based on mass balance studies comparing agricultural nitrogen inputs to nitrogen recovered in rivers. According to the IPCC Guidelines 2006 (IPCC 2006) $Frac_{LEACH}$ should be assumed as zero for dryland regions without irrigation where precipitation is lower than evapotranspiration throughout most of the year and leaching is unlikely to occur. In humid regions $Frac_{LEACH}$ should range from 0.1 to 0.8 depending on agricultural practices. Lower values than 0.3 for $Frac_{LEACH}$ can be used if more specific data are available (IPCC 2006). Many countries established country-specific values since research studies usually demonstrate lower values of $Frac_{LEACH}$ (Table 1). For example, farm scale studies and larger, catchment based studies in Ireland suggest that approximately ten percent of all applied nitrogen is lost through leaching, i.e. $Frac_{LEACH} = 0.1$

Table 1 $Frac_{LEACH}$ values smaller than default (0.3) and countries of use

Country	$Frac_{LEACH}$
Belgium	0.12
Canada	0.18
Finland	0.15
Ireland	0.10
Kazakhstan	0.06
Liechtenstein	0.20
Netherlands	0.12
New Zealand	0.07
Norway	0.18
Slovakia	0.14
Switzerland	0.20
Ukraine	0.21

(Environment Protection Agency Ireland 2011; Del Prado et al. 2006; Ryan et al. 2006; Neill 1989).

Thomas et al. (2005) found that a $Frac_{LEACH}$ value of 0.07 is appropriate for New Zealand's dairy and sheep farming systems. In contrast, the calculates for New Zealand's arable and intensive vegetable systems are close to the IPCC default value of 0.3. Switzerland and Liechtenstein use a $Frac_{LEACH}$ of 0.2, based on Prasuhn and Braun (1994), Braun et al. (1994) and Prasuhn and Mohni (2003) where long-term monitoring and modelling studies were conducted in the canton of Bern.

In Austria, the default value of 0.3 has so far been used as no accurate calculations have been available. However, in the light of the studies in other countries there is reason to believe that this value overcalculates the actual fraction of indirect soil emissions. The purpose of this paper therefore is to calculate values of $Frac_{LEACH}$ for different land uses and management practices in Austria in order to obtain reliable but upper bound calculates for the entire country.

One attractive way of estimating nitrogen leaching are lysimeters (Kroeze et al. 2003; Williamson et al. 1998; Scholefield et al. 1993; Chichester 1977). In fact, the use of direct lysimetry methods (as opposed to model calculates based on measured water content and soil water tension in different horizons) has increased in popularity in Europe in recent years due to its relatively better accuracy for long term calculations (von Unold and Fank 2008). In Austria various lysimeters are operated on both grassland and crop land which are used here to calculate the nitrogen losses.

Methodology

The IPCC ‘Tier 1’ method provides a calculation method for estimating N₂O emissions from leaching and runoff (Eq. 1)

$$N_{2O(L)} - N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) \cdot Frac_{LEACH} \cdot EF_5 \quad (1)$$

where N_{2O(L)}-N is the annual amount of N₂O nitrogen produced by leaching and runoff of nitrogen additions to managed soils (kg year⁻¹), F_{SN} is the annual amount of mineral fertilizer nitrogen applied to soils (kg year⁻¹), F_{ON} is the annual amount of managed animal manure, compost, sewage sludge and other organic nitrogen additions applied to soils (kg year⁻¹), F_{PRP} is the annual amount of urine and dung nitrogen deposited by grazing animals (kg year⁻¹), F_{CR} is the amount of nitrogen in crop residues (above and below ground, including nitrogen fixing crops, and from forage/pasture renewal, returned to soils annually (kg year⁻¹), F_{SOM} is the annual amount of nitrogen mineralised in soils associated with loss of soil carbon from soil organic matter as a result of changes in land use or land management (kg year⁻¹), Frac_{LEACH} is the fraction of all nitrogen added to or mineralised in managed soils that is lost through leaching and runoff in (kg kg⁻¹) and EF₅ is the emission factor for N₂O emissions from nitrogen leaching and runoff (kg kg⁻¹).

In total, 22 lysimeter at seven sites in Austria were used for the mass balance studies in this paper. We use the term lysimeter for a container, filled with disturbed or undisturbed soil, where percolating water is collected either gravimetrically or through suction racks with a negative soil water pressure head (www.lysimeter.at). Limitations of lysimeters usually are their inability to deal with lateral pathways of water flow.

The individual terms of Eq. 1 were measured as part of the lysimeter setup (Fig. 1). In our study, only the ratio of nitrogen leaching losses to the total N inputs was of interest, so no conversion to nitrous oxide was required. No grazing was executed and thus no N inputs of urine and dung (F_{PRP}) needs to be taken into account. For our study, F_{SOM} was kept constant because no conversion from grassland or forest to arable land was performed and organic carbon content was assumed constant over the observation period.

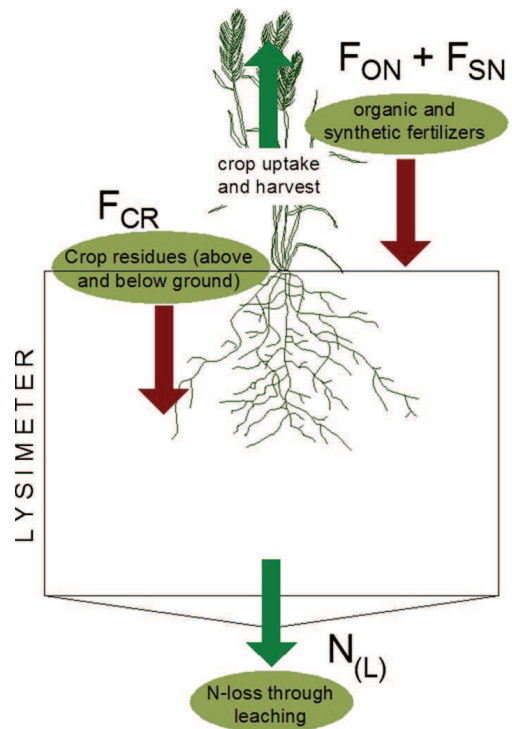


Fig. 1 Measured quantities of the nitrogen inputs and outputs (bright ellipses) of the lysimeters (see Eq. 2). Crop uptake and harvest are needed for estimating F_{CR}

Following our assumptions Eq. 1 can then be rewritten in terms of directly measurable quantities (Eq. 2).

$$Frac_{LEACH} = N_{(L)} / (F_{SN} + F_{ON} + F_{CR}), \quad (2)$$

where N(L) are the nitrogen losses through leaching. The terms of Eq. 2 were calculated from the quantity and quality of the leaching water at the individual sites.

14 out of the 22 lysimeters are located on arable land. The remaining eight lysimeters are located on grassland. They cover a wide range of soils, climatic conditions and management practices typical of Austrian agricultural land (Fig. 2). At some sites more than one lysimeter was available with differences in soil type, land use or land management.

The various lysimeter sites are maintained by different organisations. Therefore, the sizes and measuring principles differ. At some sites, a suction rack is placed at the bottom and used for water collection; at other sites a simple gravity collection of seepage water is performed. Some lysimeters have been filled with disturbed soil at their installation; some are built up of undisturbed soil monoliths. A further distinction is soil

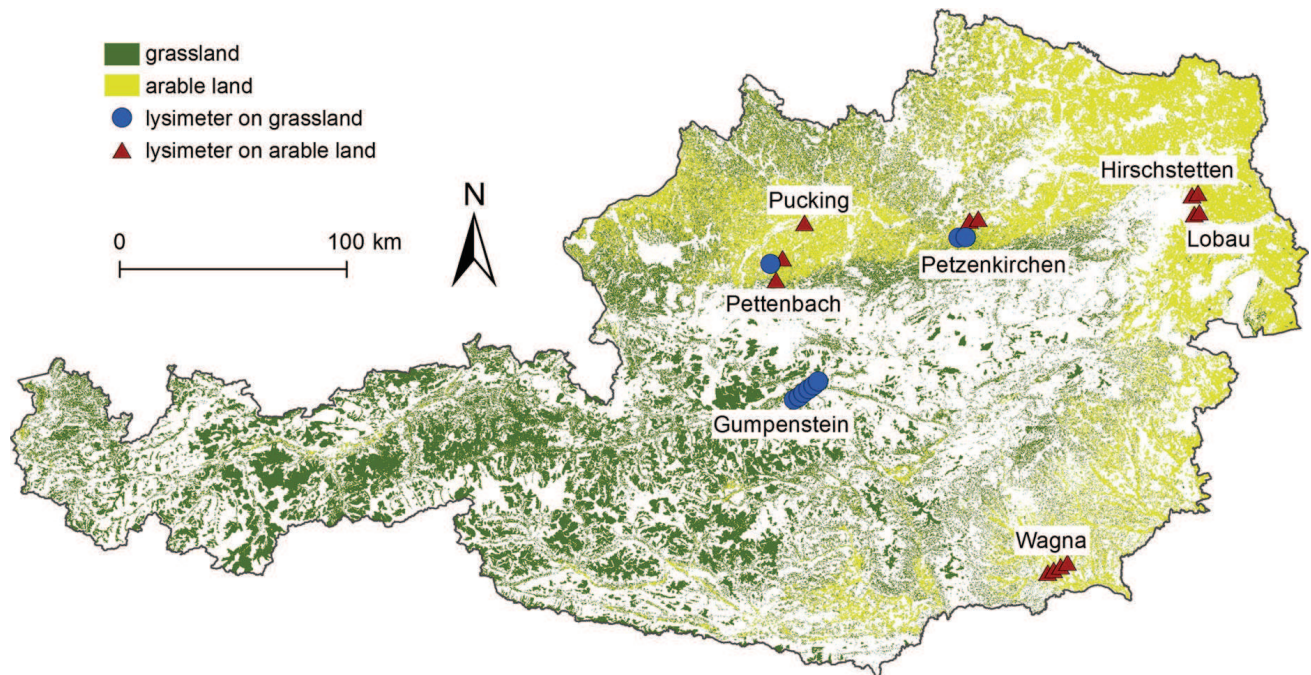


Fig. 2 Lysimeter sites and agricultural land use in Austria. Circles show sites on grassland, whereas triangles represent sites on crop land

depth and therefore the depth of water collection. The terms of the mass balance equation (Eq. 2) are all measured and can be used for estimating F_{LEACH} . An exception is F_{CR} , the plant residues. Because below ground plant residues are not determined every year at each site. They were obtained according to the IPCC guidelines by calculating the root mass as a fraction of yield at sites and years of missing data. Above ground residues are measured at most sites. Root mass as well as N-content of crops was calculated according to IPCC guidelines.

Site description

The key data of the lysimeter sites are summarized in Table 2. The description contains number of lysimeters at the site, year of installation, duration of measurement and installation method, surface area, sampling depth and sampling strategy, land use and fertilization, and—if necessary—important site specific notes.

Petzenkirchen

In Petzenkirchentwo undisturbed lysimeters (Petz and Petz_{syn}) were installed in 1989 and operated until 2001.

The lysimeters are located at 245 m a.s.l. on a low terrace of the River ‘Große Erlauf’, soil type is Eutric Cambisol (WRB 2006) from fine sediments above gravel. Typically, the ground water table is four to five meters below surface. Surface area is 0.35 m² and seepage water is collected at a depth of 110 cm under gravity conditions and analysed for nitrate and ammonia on a weekly basis (Feichtinger et al. 2004). At the Petzenkirchen site, arable land was turned to fallow in August 1994. On the Petz_{syn} site only mineral fertilizer was applied whereas on the Petz site mainly organic fertilizer was used with supplement of mineral fertilizer on demand. In 1995 both lysimeters were converted to fallow management with two cuts a year. Due to the change in land use we split the time series into two periods (1990–1994: Petz 1 and Petz_{syn} 1; 1996–2001: Petz 2 and Petz_{syn} 2). The year after the change (1995) was not included in the calculation; the effects on nitrogen leaching of the land use changes are discussed in the results section.

Wagna

In Wagna two lysimeters were filled in 1989. In 2004, the lysimeter station was renewed and both gravity lysimeters were replaced by undisturbed lysimeters with adjustable suction racks at the bottom (von

Table 2 Overview of the lysimeter sites used in this paper. Rainfall (P), annual leaching (L), surface area, sampling depth (z), lysimeter type, sampling strategy, soil types and land use are shown

Site	P (mm year ⁻¹)	L (mm year ⁻¹)	Surface area (m ²)	z (cm)	Type	Sampling	Soil type	Land use
Petz 1	723	208	0.35	110	Undis.	Gravity	Eutric Cambisol	Arable land
Petz _{syn} 1	723	297	0.35	110	Undis.	Gravity	Eutric Cambisol	
Wag _{con} 1	914	340	1	70	Disturbed	Gravity	Dystric Cambisol	
Wag _{con} 2	914	351	1	200	Undis.	Suction	Dystric Cambisol	
Wag _{bio} 1	914	228	1	110	Disturbed	Gravity	Dystric Cambisol	
Wag _{bio} 2	914	337	1	200	Undis.	suction	Dystric Cambisol	
Peba 1	1030	307	1	150	Undis.	Suction	Eutric Cambisol	
Peba 3	1030	362	1	150	Undis.	Suction	Orthic Luvisol	
Puck 1	753	339	1	150	Undis.	Suction	Eutric Cambisol	
Lob 1	534	120	1	150	Undis.	Gravity	Calcaric Fluvisol	
Lob 2	534	120	1	150	Undis.	Gravity	Calcaric Fluvisol	
Lob 3	534	120	1	150	Undis.	Gravity	Calcaric Fluvisol	
Hir _s	520	120	2	250	Disturbed	Gravity	Chernozem	
Hir _t	520	120	2	250	Disturbed	Gravity	Chernozem	
Petz 2	723	173	0.35	110	Undis.	Gravity	Eutric Cambisol	Grassland
Petz _{syn} 2	723	222	0.35	110	Undis.	Gravity	Eutric Cambisol	
Peba 2	1030	446	1	150	Undis.	Suction	Eutric Cambisol	
Gump 1	1013	464	1	150	Undis.	Gravity	Dystric Cambisol	
Gump 2	1013	584	1	150	Undis.	Gravity	Dystric Cambisol	
Gump 3	1013	1068	1	150	Undis.	Gravity	Dystric Cambisol	
Gump 4	1013	499	1	150	Undis.	Gravity	Dystric Cambisol	
Gump 5	1013	508	1	150	Undis.	gravity	Dystric Cambisol	

Unold and Fank 2008). The applied matric potential at the lysimeter bottoms equal the measured matric potential in the undisturbed soil beside the lysimeters. Surface area is 1 m² and soil type is Dystric Cambisol on a terrace of Würm ice age. Before the renewal of the lysimeters, seepage water was collected at a depth of 70 and 110 cm, respectively. In 2004 the collection depth was transferred to 2 m. The ground water table is approximately at a depth of 4 m. Management was adapted in order to understand the impact of agricultural practices in three phases. First, the typical crop rotation maize–maize–winter cereal–winter rape was investigated with respect to a regional yield increase. Since 1998 the reduction of N-fertilizers became the primary topic of interest due to increasing nitrate concentrations in the Murtal aquifer. The Murtal aquifer is a significant resource for regional drinking water supply. From 1998, no fertilisation was applied in fall. Additionally, oil pumpkin became more and

more attractive in the region. Therefore, oil pumpkin replaced winter rape in the crop rotation. One of the new lysimeters (after 2004) was run according to the guidelines for low N-input farming (BMLFUW 2006), the other one was run according to the guidelines for organic farming (EC 1991). Unfortunately, the biomass of catch crops was not recorded. Left on the fields they add to the mineralisation pool and have to be taken into account for the mass balance (Klammler and Fank 2014). For this reason, the biomass of the catch crop was modelled with Simwaser (Stenitzer 1988), a physically based model that simulates the interplay of soil water and crop development. The model was calibrated on seepage water and crop yield. The time series of Wagna was also split into two periods according to the renovation works and change of management strategy in 2004 (1990–2003: Wag_{con} 1 and Wag_{bio} 1; 2005–2012: Wag_{con} 2 and Wag_{bio} 2).

Pettenbach

In Pettenbach three undisturbed lysimeters were installed in 1995. The identical lysimeters have a surface area of one square meter and are installed at an altitude between 426 and 455 m a.s.l. on deep Eutric Cambisols (Peba 1 and Peba 2) and Orthic Luvisol (Peba 3). Water is collected at a depth of 1.5 m with a double strategy. Free draining water is measured with a tipping bucket. Additionally, a suction rack with a negative potential of approximately field capacity (60 cm water column) gives results that are more typical of field conditions (Murer 2002). The fields where the lysimeters are installed are managed by different farmers. Two of them are placed on arable land (Peba 1 and Peba 3), one is placed on grassland (Peba 2) and the management follows local practice. Additionally to the animal slurry, mineral fertilizer was applied to the Peba 1 site. Peba 2 was subject to the same fertilizer management but was used as grassland. At the Peba 3 site, organic and mineral fertilizer was applied until 1999. Later, only mineral fertilizer was used.

Pucking

In Pucking (Puck 1) a lysimeter identical in size, shape, sampling strategy and depth to those at Pettenbach site was installed in 1995 at an altitude of 288 m a.s.l. The significant difference to the lysimeters in Pettenbach is the very shallow soil (rooting depth of 60 cm). The soil type is an Eutric Cambisol. The field is used as arable land and nitrogen is applied in form of biogas slurry.

Gumpenstein

At site Gumpenstein, five identical lysimeters are in use since 2000 (Herndl et al. 2013). The undisturbed lysimeters are built of Eutric Cambisol on fluvial glacial sediments and have a surface of one square meter. Seepage water is collected in a depth of 1.5 m under gravimetric potential. The application of organic fertilizers from cow excrements was done as slurry and manure and the amount was based on local practice. No mineral fertilizer was applied. The number of cuts depends on the amount of fertilizer added with increasing amount of nitrogen added and number of cuts from Gump 1 to Gump 5.

Lobau

In the Western Marchfeld area, an intensively used agricultural region, three undisturbed lysimeters with a surface area of one square meter has been constructed in 1998. The soil is a Calcaric Fluvisol. Both measuring principles (gravity and suction rack) are used for water collection on a biweekly basis in a depth of 1.5 m. The ground water table is about 2.2–3 m below the surface and may influence the soil water budget in the natural surroundings of the lysimeters. However, the bottom of the lysimeters disconnects the water transfer from the groundwater to the lysimeter. Main goal of the installations was the evaluation of the differences between organic farming (Lob 3) and mineral fertilisation (Lob 2). Lysimeter Lob 1 is used as a control without adding any fertilizer (Erhart et al. 2007). Management and crop rotation follow the local practice, although application of mineral fertilizer was stopped in 2006. The last nitrogen input by compost was done in 2003.

Hirschstetten

At the Hirschstetten site, data of 18 lysimeters consisting of three soil types in six replicates are available from 1999 to 2002. The lysimeters had been filled horizon-wise according to the natural occurrence of the soils in the Marchfeld area. Very high clay contents and big drying cracks between the lysimeter walls and soil caused a lot of preferential flow for one soil type. This does not reflect natural behaviour and we therefore excluded six of the lysimeters from further calculations. Only two soil types (sandy Chernozem Hir_s and silty Chernozem Hir_s) with six lysimeters each were therefore used. Collection of seepage water is done in 2.5 m below ground using gravimetric potential. The surface area is two square meters (Stenitzer and Fank 2008). For this paper, mean values of the six lysimeters were used because management, crop rotation, fertilization and meteorological inputs and therefore results were similar. Only mineral fertilizer is applied.

Results and discussion

Based on the lysimeter results, harvest analyses and various accompanying measurements, the individual

terms of the nitrogen mass balance (Fig. 1) were either measured directly or calculated indirectly to derive $Frac_{LEACH}$ (Table 3).

Correction of leaching rates

At those sites where the measurements were made by gravity lysimeters, with air pressure acting on the outflow seepage rate may be underestimated, especially in dry regions (Stenitzer and Fank 2008). Therefore we replaced the leaching rates at sites Hirschstetten and Lobau by a mean annual leaching rate of 120 mm year⁻¹, which was found to be more representative in model simulations studies for this area (Stenitzer and Fank 2008). At the Wagna site, which is wetter, the difference between the two types of lysimeters was calculated as being <10 % (Stenitzer and Fank 2008). To account for this measurement

error, the seepage rates at the Wag_{con} 1 and Wag_{bio} 1 sites were therefore increased by 10 %. The same correction was applied to the other gravity lysimeters in regions with annual rainfall around or higher than 800 mm year⁻¹ (Petz 1, Petz_{syn} 1, Petz 2, Petz_{syn} 2, and Gump 1–Gump 6) following the results of Stenitzer and Fank (2008) and Dowdell and Webster (1980). Nitrogen concentrations were used as measured. The leaching rates of lysimeters with a suction rack were not corrected.

Due to this correction we artificially enlarged the nitrogen pool, because the nitrogen which is leached in theory is still in the lysimeter. The remaining nitrogen in the lysimeter might have induced higher yields and thus crop residues at the lysimeter compared to the surrounding fields. Percolating water and nitrogen may also be accumulating at the lysimeter bottom, since collection depth of the lysimeters is much higher

Table 3 Nitrogen losses through leaching ($N_{(L)_{tot}}$), nitrogen sources ($F_{SN_{tot}}$, $F_{ON_{tot}}$, $F_{CR_{tot}}$) for the whole evaluation period, values for $Frac_{LEACH}$ calculated for the whole

evaluation period ($Frac_{LEACH_{tot}}$) and as a mean of annual values ($Frac_{LEACH_{mean}}$), standard deviation of annual values (SD), number of years of observation (n)

Site	$N_{(L)_{tot}}$ (kg N ha ⁻¹)	$F_{SN_{tot}}$ (kg N ha ⁻¹)	$F_{ON_{tot}}$ (kg N ha ⁻¹)	$F_{CR_{tot}}$ (kg N ha ⁻¹)	$Frac_{LEACH_{tot}}$	$Frac_{LEACH_{mean}}$	SD	n	Land use
Petz 1	225	908	366	357	0.138	0.288	0.390	5	Arable land
Petz _{syn} 1	278	0	506	398	0.307	0.565	0.541	5	
Wag _{con} 1	638	1608	0	910	0.253	0.261	0.172	10	
Wag _{con} 2	164	548	476	1151	0.075	0.121	0.120	8	
Wag _{bio} 1	818	1370	293	1077	0.299	0.330	0.278	10	
Wag _{bio} 2	270	0	0	1625	0.166	0.309	0.398	8	
Peba 1	479	1571	769	1552	0.123	0.153	0.147	18	
Peba 3	301	116	1888	1568	0.084	0.088	0.059	18	
Puck 1	815	725	793	885	0.921	0.832	1.126	16	
Lob 1	183	0	0	1041	0.176	0.207	0.151	13	
Lob 2	248	0	285	929	0.204	0.230	0.173	13	
Lob 3	241	302	0	1087	0.173	0.240	0.230	13	
Hir _s	168	0	311	156	0.359	0.416	0.241	4	
Hir _t	163	0	373	203	0.282	0.320	0.152	4	
Petz 2	36	0	0	2279	0.016	0.018	0.015	6	Grassland
Petz _{syn} 2	18	0	0	1753	0.011	0.010	0.011	4	
Peba 2	121	955	597	708	0.054	0.057	0.033	6	
Gump 1	3	120	0	201	0.011	0.010	0.012	3	
Gump 2	5	238	0	327	0.008	0.007	0.009	3	
Gump 3	23	214	0	319	0.043	0.038	0.053	3	
Gump 4	4	311	0	377	0.006	0.006	0.002	3	
Gump 5	13	409	0	331	0.017	0.018	0.004	3	

$Frac_{LEACH_{tot}}$ (bold column in the table) is the main result of the various lysimeter sites

than rooting depth for cereals (~ 110 cm), the main crops at Hirschstetten and Lobau. In this case nitrogen will not be taken up by the plants but leached when water content is higher than field capacity. Probably both situations will occur because of the disturbed soil water regime especially at the lysimeter bottom and its interplay with drier soil horizons and plant roots.

However, the errors we cause by correcting leaching rate, are much smaller compared to the errors of the wrongly measured leaching rates. While underestimated leaching rates directly influence $\text{Frac}_{\text{LEACH}}$ (Eq. 2), enlarged nitrogen pools affect $\text{Frac}_{\text{LEACH}}$ indirectly through increased harvest and thus crop residues which are approximately one-third of harvest nitrogen.

Calculation of $\text{Frac}_{\text{LEACH}}$ (only leaching)

We used two different methods for estimating $\text{Frac}_{\text{LEACH}}$. The first method was the mass balance of the whole time series of the individual sites. Second, we calculated annual $\text{Frac}_{\text{LEACH}}$ values and their mean and standard deviation to analyse the annual variability. Of course, the sum of the ratios is not the same as the ratio of the sums, so the second method will be less representative of the long term mean.

In general, the grassland sites show significantly lower values of $\text{Frac}_{\text{LEACH}}$ compared to those on arable land (Table 3). The arithmetic mean over all grassland sites is 0.021, while on arable land it is 0.254. The highest single annual value for $\text{Frac}_{\text{LEACH}}$ on grassland was calculated for the Pettenbach site (0.11 in 1995), where mineral fertilizer was applied in addition to the manure/slurry from pig and cattle. Based on currently valid fertilizer recommendations (BMLFUW 2006) this site was affected by a surplus of fertilizer of 44 % on average.

For grassland, the temporal resolution for the evaluation plays a minor role (annually or over the entire observation period), as the variability between years is small. The annual variability is very low due to similar annual nitrogen requirements of the permanent vegetation in different years. Fluctuations may arise due to rainfall and evaporation, and a different number or different timing of mowing cycles. In Austria most of the grassland is usually grazed either permanently or after a certain number of cuts (for hay production and winter feeding). But grazing does not increase $\text{Frac}_{\text{LEACH}}$ because additional N input from grazing animals must

be taken into account, when farmers plan their fertilizer management. The Austrian fertilization guideline (BMLFUW 2006) provides thresholds, which must not be exceeded. If farmers let the animals graze, the amount of manure fertilizer must be reduced according to these guidelines. Therefore, dung and urine (from grazing animals) is not a surplus but substitute.

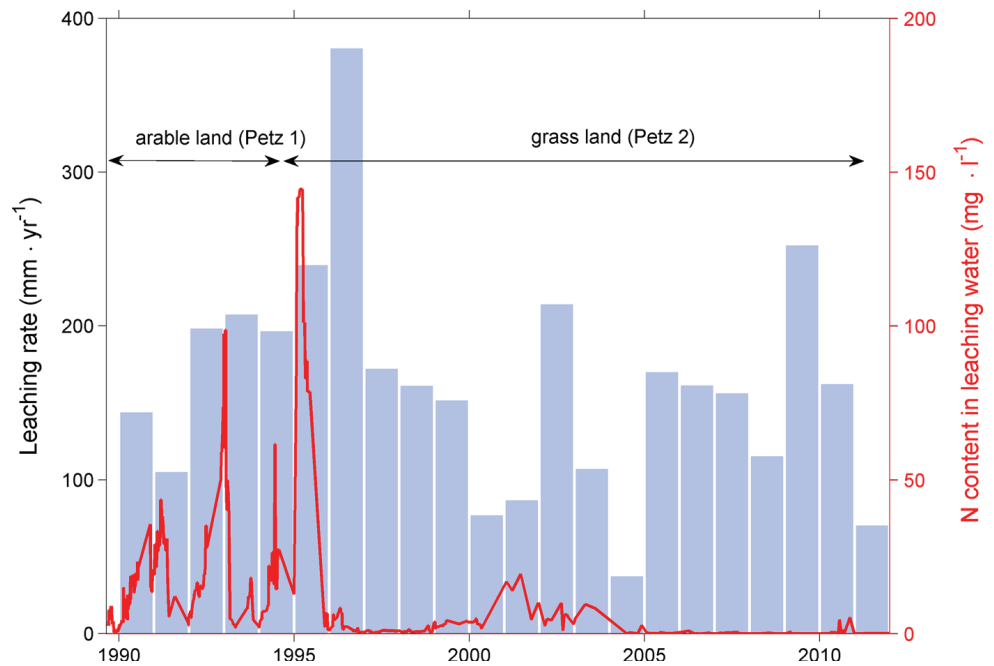
The arable sites, generally, show higher values of $\text{Frac}_{\text{LEACH}}$. They also exhibit a significant annual variability due to variations in crop rotation and fertilization rate, yields and climate conditions. In addition, the time factor of the mineralization of plant residues plays an important role (David et al. 1997). In our calculations, the mineralization pool of crop residues has been allocated to the year of harvest, although mineralization and transport will take place over a longer period. Therefore, the annual calculation of $\text{Frac}_{\text{LEACH}}$ for a single site may not be representative of the longer term mean.

Nevertheless, the annual approach is able to highlight special features of nitrogen leaching. The problem of time delay through mineralization and transport of nitrogen in the soil can be well represented at the Petzenkirchen site, as there was a land use change (Fig. 3). After harvesting of maize, the field was converted into permanent fallow in August 1994. The yields of maize in the year of change were very low leaving a large pool of nitrogen remaining in the soil. Thus, in the first months of the following year the highest nitrogen leaching rates were measured with a significant delay.

Individual years can give much larger $\text{Frac}_{\text{LEACH}}$ values than the long term average due to carry over effects between years. The highest annual values for $\text{Frac}_{\text{LEACH}}$ of all observation sites were observed at the Pucking site in those years in which soybean was grown with a maximum of $\text{Frac}_{\text{LEACH}} = 3.60$. This high value appeared because neither a mineral nor an organic fertilization was applied, which leads to a small denominator in Eq. 2. All legumes (Fabacea) tend to show high values of $\text{Frac}_{\text{LEACH}}$ due to the usually reduced or even absent fertilization.

We conducted a spearman correlation test with the factors rainfall, annual seepage, field capacity, soil depth, sampling depth, yield, N yield, N fertilization and N leached. Texture is represented through field capacity of soil. We left out chemistry which was not sufficiently available at the different sites. The correlation was done for single years, but also for the means

Fig. 3 Leaching rates and nitrogen content in seepage water for the Petzenkirchen site



of the entire observation period. Significant correlation is displayed at Table 4 in the paper.

As deducible from this table, behaviour of $Frac_{LEACH}$ is related only to a certain extent to single factors related to the environmental background of a site. Also the relationships between the single factors and $Frac_{LEACH}$ may be highly nonlinear. In the case of the relationship between $Frac_{LEACH}$ and field capacity of soil for instance, an exponential relationship was found ($r^2 = -0.28$, not shown). We then performed multiple regression including the significant factors drainage, field capacity, soil depth, N yield and N fertilization. This resulted in a r^2 of 0.47. These results indicate that site characteristics alone are only partially responsible for the value of $Frac_{LEACH}$. Much more it is depending on the actual management practices at a site as also found by Kirchmann et al. (2002), Feichtinger et al. (2008) and Jia et al. (2014).

Nitrogen loss

Although a high $Frac_{LEACH}$ indicates poor nitrogen uptake it may not necessarily indicate a high absolute nitrogen transport to groundwater. As an example, the

nitrogen losses for soybeans in Pucking were only around the average of all crops ($51 \text{ kg ha}^{-1} \text{ a}^{-1}$).

The highest nitrogen losses took place at the Wagna site during the period when the main focus of research was on increasing yields. The mean nitrogen loss was $96 \text{ kg ha}^{-1} \text{ a}^{-1}$ with a maximum for lysimeter $Wag_{bio} 1$ with $170 \text{ kg ha}^{-1} \text{ a}^{-1}$ in 1996. This can be explained by the high input of fertilizer on this site, which was 48 % higher than the N-input recommended by official guidelines from nowadays (BMLFUW 2006). In addition to high amounts of fertilizers, high annual rainfall resulting in high seepage rates increased nitrogen leaching to the groundwater (Fig. 4). Although high N losses by leaching were observed at the Wagna site, the average values of $Frac_{LEACH}$ for the four lysimeters were below (0.25 at $Wag_{con} 1$, 0.08 at Wag_{con} and 0.17 at $Wag_{bio} 2$) or close to the IPCC default value of 0.3 (0.30 at $Wag_{bio} 1$; 0.31 at $Wag_{bio} 2$).

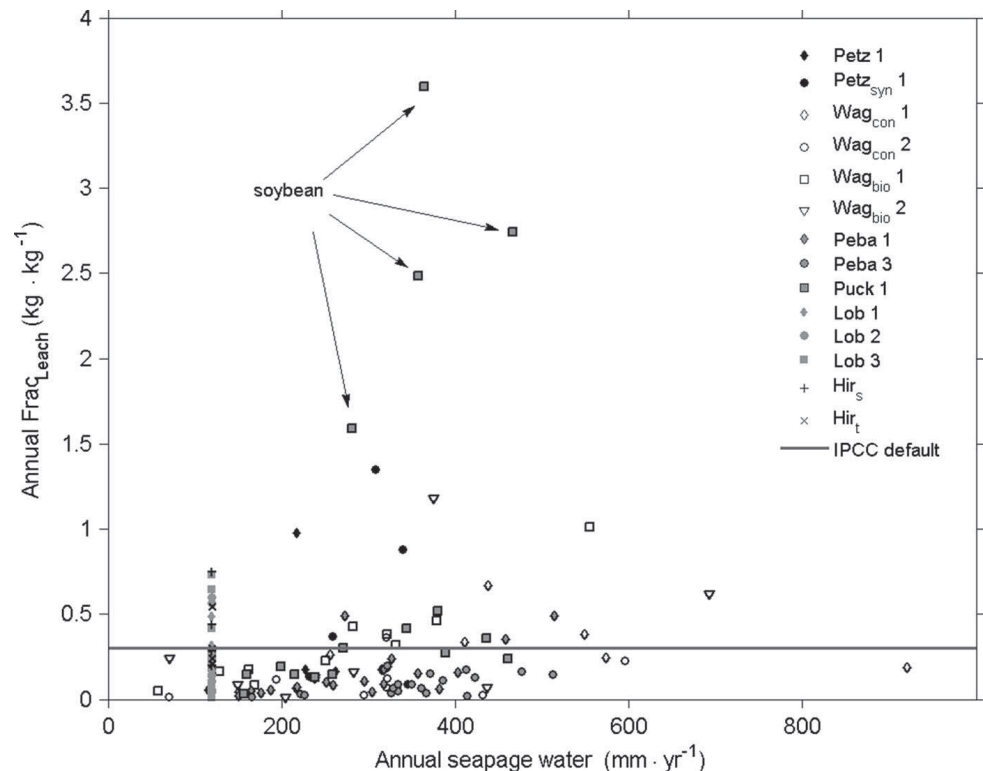
In general, high seepage water rates tend to result in both high $Frac_{LEACH}$ values and high nitrogen losses through leaching. A comparison of the sites suggests that deep soil profiles with higher available field capacity produce less nitrogen loss through leaching (see also Table 4). This can be demonstrated for the

Table 4 Correlation coefficient (Spearman) for rainfall (P), annual seepage (L), field capacity (FC), soil depth (d), sampling depth (z), nitrogen export through harvest (NH), nitrogen losses through leaching (NL) and organic fertilizer

	P	L	FC	d	z	N _H	N _L	F _{ON}
Frac _{LEACH} _{single} (n = 136)	0.35	0.65	−0.31	−0.49	−0.22	0.20	0.92	0.21
Frac _{LEACH} _{means} (n = 16)	0.23	0.38	−0.50	−0.60	−0.35	0.16	0.86	0.21

(FON) influencing FracLEACH for single years (FracLEACH single) and the means of the entire observation period (FracLEACH means)

Fig. 4 Annual values of Frac_{LEACH} as a function of annual seepage water for the lysimeters analysed. Sites closely located to each other (exhibiting similar meteorological conditions) are displayed in the same design

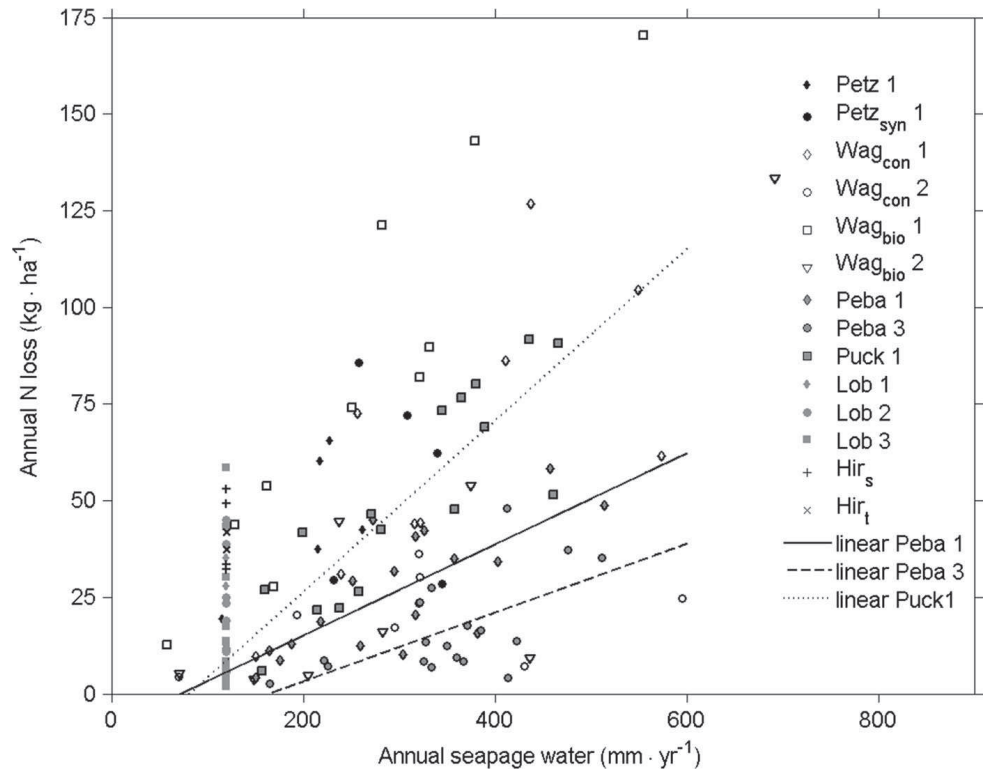


Pettenbach and Pucking sites (Fig. 5). The lysimeters are close to each other and are subject to the same climatic conditions. The trend line for nitrogen losses of the shallow Pucking site with only 60 cm topsoil (Puck 1) and a field capacity of only 112 mm within these 60 cm of topsoil due to the sandy soil is above the trend lines for Peba 1 and Peba 3 with 150 and 110 cm topsoil and 534 and 396 mm field capacity, respectively. The same annual seepage water led to higher nitrogen losses at the Puck 1 site compared to the Peba 1 and Peba 3 sites although, at Puck 1 site, only 80 % of the recommended amount of fertilizer was applied. In contrast Peba 3 and Peba 1 sites were fertilized with 95 and 122 % of the recommended amount of fertilizer.

Another aspect of exceptionally high nitrogen contents in the leaching water and high values of Frac_{LEACH} can be related to the nitrogen stock in the

soil. On the one hand, a high nitrogen stock in the soil may occur if a lot of above ground and/or below ground plant residues are incorporated into the soil for later mineralization. On the other hand, a poorly developed plant mass of the previous crop in combination with fertilizer supply may leave considerable amounts of nitrogen in the soil. When a poor plant development coincided with rainy periods, high nitrogen losses were measured. This was observed in 2008 at the Lobau site. Although the crop was potatoes which need high nitrogen fertilization, the poor development of green pea in the previous year led to nitrogen losses of 60 kg ha^{−1} a^{−1} (Lob2) and 80 kg ha^{−1} a^{−1} (Lob3). In addition to the increase of nitrogen in the soil due to incorporation of the green pea biomass, the nitrogen stock in the soil was increased by nitrogen fixation. At the Lob1 site, the

Fig. 5 Annual nitrogen losses through leaching as a function of annual seepage water on arable sites. Sites closely located to each other (exhibiting similar meteorological conditions) are displayed in the same design



zero fertilizer lysimeter at Lobau, only $20 \text{ kg ha}^{-1} \text{ a}^{-1}$ nitrogen losses through leaching were measured. However, compared to usual nitrogen losses ($14 \text{ kg ha}^{-1} \text{ a}^{-1}$ on average) at this site, the large nitrogen stock in the soil almost doubled the nitrogen losses in 2008.

Consequently, the calculated $\text{Frac}_{\text{LEACH}}$ values were significantly lower than those suggested by the IPCC Guidelines (IPCC 2006). However, in the IPCC guidelines nitrogen losses from both leaching and runoff are considered. The latter is not reflected in the lysimeters measurements since they are installed on flat fields and no surface runoff occurs.

Calculation of $\text{Frac}_{\text{LEACH}}^*$ (leaching and runoff)

For a mountainous country like Austria, any calculation of a factor $\text{Frac}_{\text{LEACH}}$ also needs to consider nitrogen losses via lateral pathways (surface runoff, subsurface runoff, drainage) (Table 5).

Nitrate concentrations of surface runoff and therefore also nitrogen losses through runoff are often small compared to the nitrate losses through leaching

(Jackson et al. 1973; Casson et al. 2008). Sharpley et al. (1987) found that 3–9 % of nitrogen fertilizer input was lost to surface runoff for an 8 year monitoring project of 20 catchments in Texas and Oklahoma. However, these results refer to different agroecological environments compared to Austrian conditions. Unfortunately, the data base for calculation of a runoff component for $\text{Frac}_{\text{LEACH}}$ in Austria is not sufficiently developed yet. To consider losses by runoff we therefore used results of a simulation study to derive pathways of nitrogen losses at the scale of all of Austria (BMLFUW 2011). We added simulated nitrogen inputs to rivers from overland flow ($10,321 \text{ t year}^{-1}$), snow melt (535 t year^{-1}) and drainages (2732 t year^{-1}) and divided this amount with simulated inputs from groundwater ($45,425 \text{ t year}^{-1}$), resulting in a contribution of 30 % of the total nitrogen losses for pathways related to lateral flow processes. The number of 30 % can be considered an upper bound of possible losses because BMLFUW (2011) also included emissions from forests, alpine regions and the atmospheric nitrogen input in addition to the input data which would be

Table 5 Measured nitrogen losses through leaching ($N_{(L)\text{leaching}}$), calculated nitrogen losses through runoff ($N_{(L)\text{runoff}}$), total nitrogen losses through leaching and runoff ($N_{(L)}$), nitrogen sources ($F_{SN} + F_{ON} + F_{CR}$), corrected values for $\text{Frac}_{\text{LEACH}}$ ($\text{Frac}_{\text{LEACH}}^a$) and land use

Site	$N_{(L)\text{leaching}}$ (kg N ha ⁻¹)	$N_{(L)\text{runoff}}$ (kg N ha ⁻¹)	$N_{(L)}^a$ (kg N ha ⁻¹)	$F_{SN} + F_{ON} + F_{CR}$ (kg N ha ⁻¹)	$\text{Frac}_{\text{LEACH}}^a$	Land use
Petz 1	225	68	293	1632	0.180	Arable land
Petz _{syn} 1	278	83	361	904	0.399	
Wag _{con} 1	638	191	830	2518	0.329	
Wag _{con} 2	164	49	213	2175	0.098	
Wag _{bio} 1	818	245	1064	2740	0.388	
Wag _{bio} 2	270	81	351	1625	0.216	
Peba 1	479	144	623	3892	0.160	
Peba 3	301	90	391	3572	0.109	
Puck 1	815	245	1060	2403	0.441	
Lob 1	183	55	238	1041	0.229	
Lob 2	248	74	323	1214	0.266	
Lob 3	241	72	313	1389	0.225	
Hir _s	168	50	218	467	0.467	
Hir _t	163	49	211	575	0.367	
Petz 2	36	11	47	2279	0.020	
Petz _{syn} 2	18	6	24	1753	0.014	
Peba 2	121	36	157	2260	0.070	
Gump 1	3	1	4	322	0.014	
Gump 2	5	1	6	564	0.010	
Gump 3	23	7	30	533	0.056	
Gump 4	4	1	5	688	0.008	
Gump 5	13	4	17	740	0.022	

Table 6 Mean $\text{Frac}_{\text{LEACH}}$ (only leaching) and mean modified $\text{Frac}_{\text{LEACH}}^a$ (leaching and runoff) of all arable and grassland sites calculated in this paper from lysimeter data

	$\text{Frac}_{\text{LEACH}}$	$\text{Frac}_{\text{LEACH}}^a$
Arable land	0.254	0.277
Grassland	0.021	0.027
Austria overall	0.135	0.150

relevant for the IPCC's indirect soil emissions calculation. Additionally, these nitrogen emissions may not be considered as leaching losses but as inputs to rivers with reduced nitrogen amounts due to the process of denitrification. Unfortunately denitrification information is not available at present. Including denitrification would further reduce the contribution of lateral pathways.

Conclusions

The evaluation of nitrogen leaching from various lysimeter sites in Austria shows that under local management practices $\text{Frac}_{\text{LEACH}}$ is smaller than the default value of 0.3 suggested by IPCC rules. In particular, calculated $\text{Frac}_{\text{LEACH}}$ for grassland is 0.021. For arable sites, $\text{Frac}_{\text{LEACH}}$ values were around 0.254 (Table 6). With a ratio of nitrogen losses through runoff to nitrogen losses through leaching of 0.30 (BMLFUW 2008), the modified arithmetic mean for $\text{Frac}_{\text{LEACH}}$ for arable land and grassland is 0.277 and 0.027, respectively. Arable land and grassland cover 49 and 51 % of the total agricultural area in Austria. Assuming that the results of the lysimeter studies represent management practices, soil properties and climatic conditions that are representative of Austria as a whole, the overall value for $\text{Frac}_{\text{LEACH}}$ for

Austria then is 0.15. This is a considerably smaller value than the default value of $Frac_{LEACH}$ proposed by IPCC.

This calculation of the nitrogen losses through leaching and runoff may certainly be further improved by upscaling of site results using more detailed regional characteristics of land management and soil properties. A comparison of $Frac_{Leach}$ to main environmental parameters has revealed that the complexity of the interactions between these parameters is the main driver of changing values for $Frac_{Leach}$. As a basis for an upscaling of the results obtained, process based models may be employed which are able to deal with a large variety of different climate–soil–land management interactions. These models may be calibrated using results of this lysimeter study. Further research is also necessary for hilly land, where nitrogen losses occur through a combination of seepage, subsurface flow and surface flow.

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References

- BMLFUW-Bundesministerium für Land-und Forstwirtschaft, Umwelt und Wasser (2006) Richtlinien für die Sachgerechte Düngung. Anleitung zur Interpretation von Bodenuntersuchungsergebnissen in der Landwirtschaft. 6. Auflage, Bundesministerium für Land-und Forstwirtschaft, Umwelt und Wasser, 79 S., Wien
- BMLFUW-Bundesministerium für Land-und Forstwirtschaft, Umwelt und Wasser (2011) Stoffbilanzmodellierung für Nährstoffe auf Einzugsgebietsebene als Grundlage für Bewirtschaftungspläne und Maßnahmenprogramme. Bundesministerium für Land-und Forstwirtschaft, Umwelt und Wasser, 190 S., Wien
- Braun M, Hurni P, Spiess E (1994) Phosphor-und Stickstoffüberschüsse in der Landwirtschaft und Para-Landwirtschaft : Abschätzung für die Schweiz und das Rheineinzugsgebiet der Schweiz unterhalb der Seen. Schriftenreihe der FAC Liebefeld 18, Bern
- Casson JP, Olson BM, Little JL, Nolan SC (2008) Assessment of environmental sustainability in Alberta's agricultural watersheds project, Volume 4, Nitrogen loss in surface runoff. Alberta Agriculture and Rural Development: Lethbridge, p 71
- Chichester FW (1977) Effects of increased fertilizer rates on nitrogen content of runoff and percolate from monolith lysimeters. *J Environ Qual* 6:211–217. doi:10.2134/jeq1977.00472425000600020023x
- David MB, Gentry LE, Kovacic DA, Smith KM (1997) Nitrogen balance in and export from an agricultural watershed. *J Environ Qual* 26:1038–1048. doi:10.2134/jeq1997.00472425002600040015x
- Del Prado A, Brown L, Schulte R, Ryan M, Scholefield D (2006) Principles of development of a mass balance N cycle model for temperate grasslands: an Irish case study. *Nutr Cycl Agroecosyst* 74:115–131. doi:10.1007/s10705-005-5769-z
- Dowdell RJ, Webster CP (1980) A lysimeter study using nitrogen-15 on the uptake of fertilizer nitrogen by perennial ryegrass swards and losses by leaching. *Eur J Soil Sci* 31:65–75. doi:10.1111/j.1365-2389.1980.tb02065.x
- European Council (EC) (1991) Council regulation No 2092/91 of June 1991 on organic production of agricultural products and indications referring thereto on agricultural products and foodstuff. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1991R2092:20080514:EN:PDF>. Accessed 7 Apr 2014
- Environment Agency Austria (2013) Austria's national inventory report 2013—agriculture (CRF Sector 4). Environment Agency Austria, Vienna, pp 260–322
- Environmental Protection Agency Ireland: National inventory report (2011). Greenhouse gas emissions 1990–2009 reported to the UPFCCC. Wexford
- Erhart E, Feichinger F, Hartl W (2007) Nitrogen leaching losses under crops fertilized with biowaste compost compared with mineral fertilization. *J Plant Nutr Soil Sci* 170: 608–614. doi:10.1002/jpln.20062518
- Feichtinger F, Dorner J, Aigner F (2004) Durchschnittliche Versickerungsmengen und bewirtschaftungsbedingte Stickstoffausträge im Alpenvorland Niederösterreichs. Schriftenreihe des Bundesamt für Wasserwirtschaft 20:79–90
- Feichtinger F, Strauss P, Lescot JM, Kaljonen M, Hofmacher G (2008) Integrated assesment of groundwater protection using agricultural best management practices—a nitrogen case study. *Die Bodenkultur* 59(1–4):149–164
- Herndl M, Schink M, Kandolf M, Bohner A, Buchgraber K (2013) Nährstoffauswaschung im Grünland in Abhängigkeit vom Wirtschaftsdüngungs- und Nutzungssystem, Conference Proceeding: 15. Dumpensteiner Lysimetertagung 2013, Raumberg-Gumpenstein, 25–30, ISBN: 978-3-902559-90-6
- IPCC (2000) Good practice guidelines and uncertainty management in national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme. In: Penman J, Kruger D, Galbally I, Hiraishi T, Nyenzi B, Emmanul S, Buendia L, Hoppaus R, Martinsen T, Meijer J, Miwa K, Tanabe K (eds) IGES, Japan, ISBN 4-88788-000-6
- IPCC (2006) IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme. In: Eggelston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) IGES, Japan, ISBN 4-88788-032-4
- Jackson WA, Asmussen IE, Hauser EW, White AW (1973) Nitrate in surface and subsurface flow from a small agricultural watershed. *J Environ Qual* 2:480–482. doi:10.2134/jeq1973.00472425000200040017x
- Jia XC, Shao LJ, Liu P, Zhao BQ, Gu LM, Dong ST, Bing SH, Zhang JW, Zhao B (2014) Effect of different nitrogen and irrigation treatments on yield and nitrate leaching of

- summer maize (*Zea mays* L.) under lysimeter conditions. *Agric Water Manag* 137:92–103
- Kirchmann H, Johnston AEJ, Bergstrom LF (2002) Possibilities for reducing nitrate leaching from agricultural land. *Ambio* 31(5):404–408
- Klammler G, Fank J (2014) Determining water and nitrogen balances for beneficial management practices using lysimeters at Wagna test site (Austria). *Sci Total Environ* 449:448–462. doi:10.1016/j.scitotenv.2014.06.009
- Kroeze C, Aerts R, van Breemen N, van Dam D, van der Hoek K, Hofschreuder P, Hoosbeek M, de Klein J, Kros H, van Oene H, Tietema A, van der Veeren R, de Vries W (2003) Uncertainties in the fate of nitrogen I: an overview of sources of uncertainty illustrated with a Dutch case study. *Nutr Cycl Agroecosyst* 66:43–69. doi:10.1023/A:1023339106213
- Mosier A, Kroeze C, Nevison C, Oenema O, Seitzinger S, van Cleemput O (1998) Closing the global N₂O budget: nitrous oxide emissions through the agricultural nitrogen cycle—OECD/IPCC/IEA phase II development of IPCC guidelines for national greenhouse gas inventory methodology. *Nutr Cycl Agroecosyst* 52:225–248. doi:10.1023/A:1009740530221
- Murer E (2002) Erfassung und Bewertung der Sickerwasserquantität und—qualität im Pilotprojekt zur Grundwassersanierung in Oberösterreich. Monolithische Feldlysimeter. Schriftenreihe des Bundesamtes für Wasserwirtschaft 16:112–139
- Neill M (1989) Nitrate concentrations in river waters in the south-east of Ireland and their relationship with agricultural practice. *Water Res* 23:1339–1355. doi:10.1016/0043-1354(89)90073-0
- Prasuhn V, Braun M (1994) Abschätzung der Phosphor- und Stickstoffverluste aus diffusen Quellen in die Gewässer des Kantons Bern. Schriftenreihe der FAC Liebefeld 17. Bern
- Prasuhn V, Mohni R (2003) GIS-gestützte Abschätzung der Phosphor- und Stickstoffeinträge aus diffusen Quellen in die Gewässer des Kantons Bern. FAL, interner Bericht z.H. Amt für Gewässerschutz und Abfallwirtschaft, Kanton Bern. Zürich-Reckenholz
- Ryan M, Brophy C, Connolly J, McNamara K, Carton OT (2006) Monitoring of nitrogen leaching on a dairy farm during four drainage seasons. *Irish J Agric Food Res*. 45: 115–134. <http://www.jstor.org/stable/25562571>. Accessed 28 Aug 2014
- Scholefield D, Tyson KC, Garwood EA, Armstrong AC, Hawkins J, Stone AC (1993) Nitrate leaching from grazed grassland lysimeters: effects of fertilizer input, field drainage, age of sward and patterns of weather. *Eur J Soil Sci* 44:553–749. doi:10.1111/j.1365-2389.1993.tb02325.x
- Sharpley AN, Smith SJ, Naney JW (1987) Environmental impact of agricultural nitrogen and phosphorus use. *J Agric Food Chem* 35:812–817
- Stenitzer E (1988) Simwaser—Ein numerisches Modell zur Simulation des Bodenwasserhaushaltes und des Pflanzenertrages eines Standortes. Mitteilungen aus der Bundesanstalt für Kulturtechnik und Bodenwasserhaushalt 31, Petzenkirchen
- Stenitzer E, Fank J (2008) Schwerkraft-versus Unterdrucklysimeter—eine Simulationsstudie. In diffuse Einträge in das Grundwasser: Monitoring—Modellierung—Management, Landwirtschaft und Wasserwirtschaft im Fokus zu erwartender Herausforderungen. Beiträge zur Hydrogeol 56:114–118 Graz
- Thomas SM, Ledgard SF, Francis GS (2005) Improving calculates of nitrate leaching for quantifying New Zealand's indirect nitrous oxide emissions. *Nutr Cycl Agroecosyst* 73:213–226. doi:10.1007/s10705-005-2476-8
- von Unold G, Fank J (2008) Modular design of field lysimeters for specific application needs. *Water Air Soil Pollut Focus* 8:233–242. doi:10.1007/s11267-007-9172-4
- Williamson JC, Taylor MD, Torrens RS, Vojvodic-Vukovic M (1998) Reducing nitrogen leaching from dairy farm effluent-irrigated pasture using dicyandiamide: a lysimeter study. *Agric Ecosyst Environ* 69:81–88. doi:10.1016/S0167-8809(98)00099-1