N Leaching in Intensive Agriculture with Plastic Mulching under Monsoon Climate in South Korea: a Suction Lysimeter Study

Kettering, Janine (1); Ruidisch, Marianne (2); Kiese, Ralf (3); Kuzyakov, Yakov (1,4)

(1) Department of Agroecosystem Research, University of Bayreuth, 95440 Bayreuth, Germany, janine.kettering@uni-bayreuth.de
(2) Department of Soil Physics, University of Bayreuth, 95440 Bayreuth, Germany, ruidisch@uni-bayreuth.de
(3) Karlsruhe Institute of Technology, 82467 Garmisch-Partenkirchen, Germany, ralf.kiese@kit.edu
(4) Department of Soil Science of Temperate Ecosystems, University of Göttingen, 37077 Göttingen, Germany, kuzyakov@gwdg.de

Abstract: Excessive N fertilization and the heavy monsoon rains during the cropping season together with predominantly sandy soils in Haean Catchment (South Korea) are predestined for high N leaching losses leading to water pollution. The purpose of this study was to investigate the dynamics of N loss with leaching in intensive dryland cropping systems with ridge-cultivation and plastic mulching. We investigated (1) the fate of fertilizer N, (2) the residual effect of N in the soil profile, and (3) the N downward movement with percolation, using the ^{15}N fertilizer method in a summer radish system under conventional management. Since N leaching was not expected during the dry and cold winter, we conducted the field experiment during the cropping season. In order to determine optimal gains in ecosystem services, namely production of agricultural crops versus limited impacts on water quality, N dynamics were examined within a range of fertilization levels ranging from 50 to 350 kg N ha^{-1}. New elements of this experiment were 1) the dicotyledonous root crop species, 2) the adaption of local farming methods of ridge-cultivation and plastic mulching, and 3) the heavy rains of the East-Asian summer monsoon. A similar biomass production compared to the highest fertilizer application rates, but with a notably higher recovery of tracer and fairly lower nitrate concentrations in seepage over the cropping season was shown by rate N150.

Keywords: *N leaching, N retention, sandy soils, summer monsoon, N use efficiency, stable isotope, suction lysimeter*

1. Introduction

1.1 N Leaching in Agroecosystems

Nitrogen cycles in intensively managed agricultural ecosystems have received more attention than those in natural ecosystems as it is one of the most challenging nutrient problems in agriculture (Liu et al. 2003). Crop production and increasing N fertilization beyond crop needs interfere in water and nutrient cycling. N leaching can reach considerable levels, especially in intensively cultivated areas with high precipitation and light textured soils (Di/Cameron 2002) and is often considered as the main N loss pathway on sandy soils (Liu et al. 2003).

In South Korea, the agricultural system shifted over the last 40 years towards an intensive agriculture, which heavily depends on high mineral fertilizer N inputs. In Gangwon Province, N application rates indicated by farmers of the Haean Catchment range between 150 and 450 kg N ha^{-1} yr^{-1}. N budgets with high N surpluses and fairly low N crop use efficiencies have been described for the main crop systems in Haean Catchment and for South Korea (Kettering in preparation 2011, Bashkin et al. 2002). N surpluses are considered as indicators of the potential losses from the systems (Oenema et al. 2003). 75% up to > 94% of these N surpluses are assumed to be lost from the system by processes such as leaching, denitrification, and ammonia volatilization (Watson et al. 2002). The heavy rainfalls of the monsoon season which follow the high fertilizer N application are likely to increase potential N losses through leaching. In Haean Catchment, we hypothesize that 90% of the N losses occur by leaching due to no significant N storage in the light textured soils with little water and nutrient retention capacity.

Di/Cameron (2002) and Boumans et al. (2005) showed that N leaching depends on various local factors such as on climate (arid < humid), soil type (fine-textured soil < coarse-textured soil), and agricultural management (natural system < agricultural system). The amount of N leaching under various field conditions has been extensively studied for different parts of the world (Richter/Roelcke 2000, Boumans et al. 2005, Davis et al. 2003, Ju et al. 2009). However, no data of direct field measurements are available for intensive Korean agriculture with ridge-cultivation and plastic mulching under East-Asian summer monsoon climate. Therefore, we conducted an on-field suction lysimeter study to investigate the impact of different fertilizer rates as well as of ridge-cultivation systems with plastic mulching on N leaching losses. The most common field method for extracting soil water is the use of porous suction lysimeter often in combination with measurements of water balance (Paramasivam et al. 2001, Potschin 1999). A good overview about the topic of soil water extraction with suction lysimeter is written by Grossmann (Grossmann et al. 1987, Grossmann/Udluft 1991) and Potschin (1999).

In the present study, we investigated (1) the fate of fertilizer N, (2) the residual effect of N in the soil profile, and (3) the N downward movement with percolation, using the ^{15}N fertilizer method in a summer radish system under conventional management. Since N leaching was not expected during the dry and cold winter, we conducted the field experiment only during the cropping season.

2. Materials and Methods

2.1 Study Site and Experimental Design

The field experiment was conducted on a typical Korean Anthrosol at the Punchball Tongil Agricultural Experimental Farm (38.3°N, 128.14°E, 420 m asl) of the Haean-myun Catchment in Yanggu County, Gangwon Province, South Korea. Soil texture was loamy sand from 0-40 cm and sandy loam from 40-60 cm, with a bulk density of 1.27 g cm^{-3} at 0-60 cm. The study area falls within the East-Asian monsoon area and has an 11-year average annual air temperature of 8.5°C and an annual precipitation of approximately 1577 mm, with 70% occurring as heavy rains in June, July and August and 90% within the cropping season from April to October.

Four treatments were defined: N50, N150, N250, and N350, reflecting the application of 50, 150, 250, and 350 kg N ha^{-1}, respectively. The plots (49 m^2 in area, 7x7 m) were arranged in a randomized block design with 3 replicates. The ^{15}N-labeling experiment was performed in micro plots of around 1 m^2 (125x75 cm). Low enriched $K^{15}NO_3$ (10 at%) was added as a tracer to follow the fate of the applied fertilizer and to document its progressive distribution and potential loss. Care was taken to add the N solution of 3.48 kg ^{15}N/ha homogeneously to the plots. Each microplot contained one furrow and one ridge, including six labeled radish plants. To estimate N loss in seepage water over the cropping season, suction lysimeters combined with a soil hydrological monitoring network of daily read-out tensiometers and ECH2O logger (5TE soil moisture, temperature and EC, Decagon Devices, USA) connected with datalogger (EM50, Decagon Devices, USA) was installed.

2.2 Sampling and Analysis

Aboveground and belowground biomass was measured manually in each ^{15}N plot at day 25, 50 and 75. Time is expressed as days after sowing. Four labeled plants in each plot were harvested to determine fresh weight (FW) and dry matter (DM). Immediately after harvest, the FW was measured, and DM of the plant parts was determined after drying at 70°C for at least 48h. An aliquot of each plant part was ground with a ball mill (< 0.25 mm) (Brinkman Retsch, MM2 Pulverizer Mixer Mill, Germany) to a fine powder for isotopic analysis and stored until further analysis.

Soil samples were taken (three from each ^{15}N plot) from 0-60 cm at day 25, 50 and 75 with a soil corer (diameter 5cm, length 1m). Soil sampling and analysis was done separately for ridges and furrows. Soil cores were divided into three soil depths (0-20 cm, 20-40 cm, 40-60 cm) and combined to form one composite sample per plot, location and depth. The pooled soil samples were dried at 60°C and sieved (<2 mm). An aliquot of each soil sample was ground with a ball mill (< 0.25 mm) (Brinkman Retsch, MM2 Pulverizer Mixer Mill, Germany) to fine powder for isotopic analysis and stored until further analysis.

To determine N loss with seepage water, the collecting flasks of each sampling depth and location were separately emptied for chemical analysis on a weekly basis. Samples for NO_3-N and NH_4-N concentrations were refrigerated at 5°C within 2h of collection and analyzed within 2 days in the field laboratory with Spectroquant® quick tests based on the photometric method (Nitrate test photometric, DMP 0.10 - 25.0 mg/l NO_3-N 0.4 - 110.7 mg/l NO_3 Spectroquant® ; Ammonium test photometric 0.010 - 3.00 mg/l NH_4-N 0.013 - 3.86 mg/l NH_4 Spectroquant®, MERCK, South Korea) for photometer (LP2W Digital Photometer, Dr. Lange, Germany).

3. Preliminary Results

3.1 Plant Biomass, Recovery in Crops and Fertilizer NUE

Biomass production and N crop uptake increased with increasing fertilizer N application rates. The maximum radish production was achieved with 350 kg N ha^{-1} (131 t ha^{-1}). Yet, rate N150, N250, and N350 lie all within the same range (>120 t ha^{-1}). Only rate N50 deviates from this range with a production of only 105 t ha^{-1}. Similar results can be found for the N uptake by crops. However, rate N150 deviates from the previous pattern. While it shows the same development as the higher rates of N until day 50 after seed, only little N is further taken up by the crops until the final harvest. Looking at the tracer uptake by plants, we found that the highest recovery rates were generally observed at the lower fertilizer N application rates (N50, N150) (Figure 1). However, for these rates, we found the tracer uptake to be highest at day 50, with 36% and 30%, respectively. In contrast, the higher fertilizer N rates (N250, N350) show continuously increasing uptake of tracer over the entire 75 days of growth, but a lower total N uptake at the final harvest. At day 75, the total recovery rate which reflects the fertilizer use efficiency ranged between 20% (Rate N250) and 32% (Rate N50). We couldn't identify reasons for the exceptionally low uptake of tracer at rate N250. The mean fertilizer use efficiency of all rates amounts to 27%, excluding the differing rate N250 it amounts to 30%.

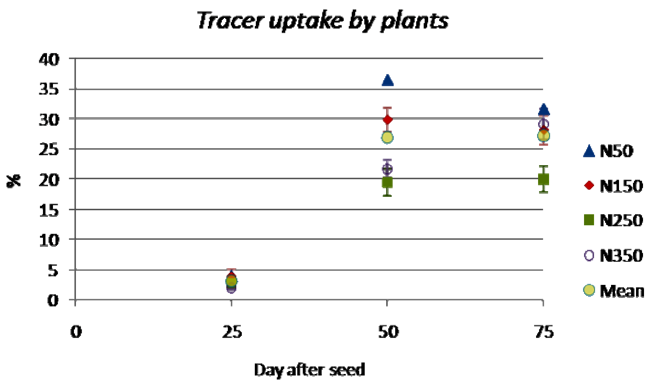

Figure 1. Tracer uptake by plants

3.2 Retention in Soil

We found the retention of tracer in soil to be highest at the two lowest rates of N at all three sampling dates (Figure 2). The retention rate of rate N50 at day 75 (26%) is even found to be higher than the retention of the rates N250 and N350 at the first sampling date, with 14% and 6 % retention in soil, respectively. Looking at the three different sampling dates, a considerable decrease of the retention rates from day 25 to 50 can be observed, whereas from day 50 to 75 a slight increase can be found.

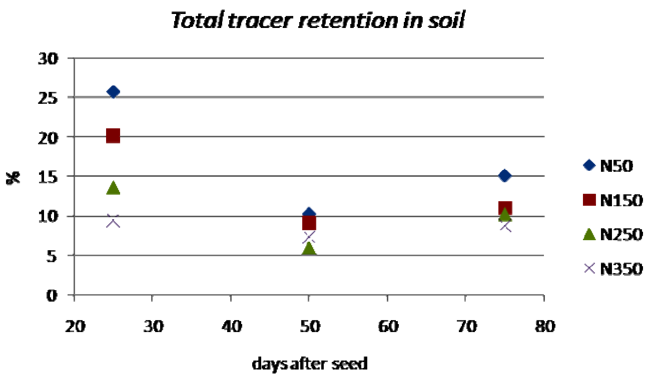

Figure 2. Tracer retention in soil

Looking at the distribution of the retention in soil in relation to different soil profile depths and different locations, we found the highest retention rate in the top layer of the ridges (0-20 cm) for all fertilizer N rates. By comparing the respective depths of both locations, we observed considerable higher retention in the ridges than in the furrows. Further, the tracer retention in soil decreases with increasing soil depth. According to this, the highest tracer retention of all depths and locations was found in the top layer of the ridges from rate N50 and N 150 at day 25, whereas the lowest retention was identified at the 20-40 cm layer of the furrows.

3.3 Soil Water N Concentration

We found a linear increase of nitrate concentrations with increasing fertilizer N rates (figure 3). This is characteristic for all soil depths and locations. The highest NO_3-N concentration was documented for rate N250 and N350 with 256 mg l^{-1} and 241 mg l^{-1}, respectively. While the concentrations of the lower N application rates at the beginning of the measurements can be as high as for the rates N250 and N350, their decrease is more rapidly and steadily and they finally reach concentrations < 10 mg l^{-1} for all depths and locations at the end of July. On the contrary, the decrease of NO_3-N concentrations for the higher rates is less rapid and steady and the final nitrate concentrations show a higher standard (> 10 mg l^{-1}). Looking at the different sampling depths and locations, we found a very similar temporal pattern for ridges and furrows and sampling depths. However, the nitrate concentrations decline with increasing sampling depth for all four fertilizer N treatments but show similar values for the respective location of each depth. On a season basis, the mean nitrate concentration for the four fertilizer N application rates increased in the order N50 (53 mg NO_3 l^{-1}) < N150 (67 mg NO_3 l^{-1}) < N250 (119 mg NO_3 l^{-1}) < N350 (122 mg NO_3 l^{-1}). Mean values of all N application rates show the highest concentrations for the top layer of the ridges (115 mg NO_3 l^{-1}), followed by the deeper layers of the ridges and the furrows with a concentration of 84 mg NO_3 l^{-1} and 81 mg NO_3 l^{-1}, respectively.

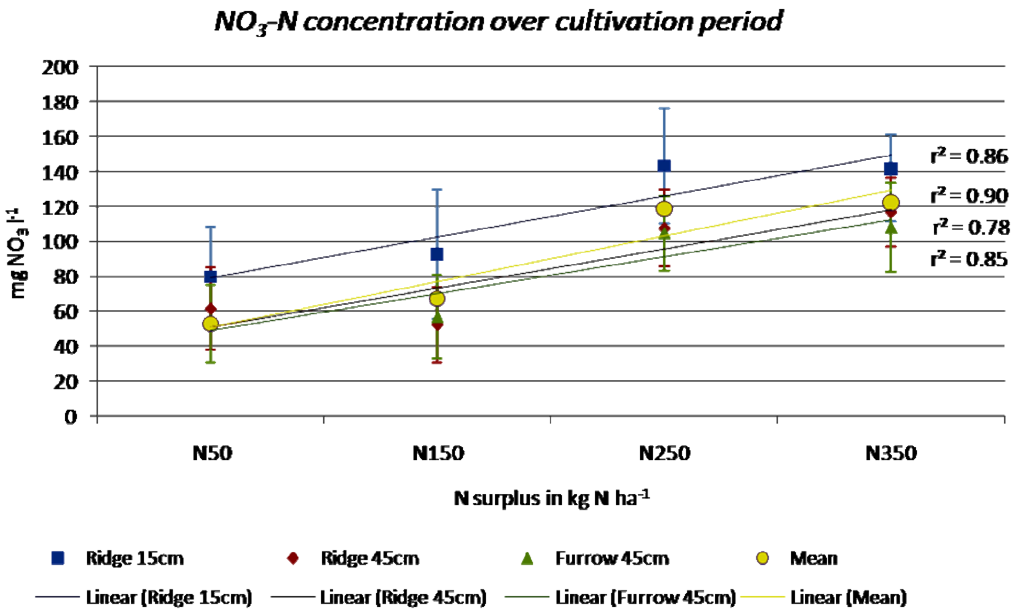

Figure 3. Mean nitrate concentrations in seepage over the cropping season

4. Discussion

The results for biomass production and N recovery in crops suggest that at rate N50 and N150 most of the fertilizer N is lost until day 50 and no further or only little N uptake can take place until the final harvest. The results of the tracer uptake by plants support this assumption. While the rates N50 and N150 show the highest recovery rates at day 50, the higher application rates of N continuously increase their uptake until the final harvest. The assumption is also second by the trends in nitrate concentration in seepage. While the concentrations of the lower N application rates at the beginning of the measurements can be as high as for the rates N250 and N350, their decrease is more rapidly and steadily and they finally reach concentrations < 10 mg l^{-1} already around day 40. However, the lower rates of N show generally a higher tracer recovery in crops and therefore a higher fertilizer N use efficiency.

While ^{15}N isotopes are an invaluable tool to estimate fertilizer N use efficiency, studies with ^{15}N fertilizers have often shown that fertilizer application increases plant uptake of unlabeled soil N because of mineralization-immobilization turnover. For soils low in native N, ^{15}N recovery may be lower in case immobilization of fertilizer nitrogen occurs to a significant extent. This pool substitution could lead to an underestimate of fertilizer N uptake by plants (Eviner et al. 2000, Vlek/Byrnes 1986). Finck (1992) considered that the proportions of fertilizer N taken up by the crop during the season of application are 50-70% under controlled conditions. Yet, fertilizer sources are not used efficiently in practice, and therefore plant uptake of fertilizer seldom exceeds 50% of the applied N (Peoples et al. 1995). Taking into account a slight underestimation of our results and an overestimation of Finck's results, our calculated mean fertilizer N use efficiency of 30% is somewhat lower as the range of common N uptake by crops. The high fertilizer losses within the first weeks are most likely responsible for the poor performance.

Tracer retention in soil decreased rapidly at the beginning of the cropping season, resulting from plant uptake and high leaching losses. Already at day 25 after seed, the major part of the fertilizer has been lost. The final total retention of the applied tracer in soil at the end of the experiment increased in the order 9% (N350) < 10% (N250) < 11% (N150) < 15% (N50). We found the retention rate be highest at the two lowest rates of N at all three sampling dates. We also observed considerable higher tracer retention in the ridges than in the furrows. Furthermore, the tracer retention rate in soil decreased with increasing soil depth. Only negligible quantities (< 2%) of ^{15}N were found below 20 cm at the end of the growing season. This corresponds with the findings of Vlek/Byrnes (1986), who found fertilizer N remaining in the soil was mainly present in the top 15 cm, even in the most permeable soils (Vlek/Byrnes 1986). The higher retention in ridges can probably be explained with the method of fertilizer application. While it is evenly distributed over the entire field at the application itself, the main part of the fertilizer accumulates in the ridges during the following process of ridge creation. Additionally, the ridges are covered with the black cover which might protect the tracer from leaching. Similar results have been stated in a research review from Power et al. (2001). Hatfield et al. (1998) concluded that in general, ridge-till systems reduced agrichemical leaching and adverse effects on water quality, whereas Karlen et al. (1998) stated that ridge tillage with excess N application will not reduce potential for water degradation.

In seepage, the major part of the variations within the nitrate concentrations can be traced back to to the fact, that we applied different fertilizer N rates. NO_3-N concentrations increased with increasing fertilizer rates, with concentrations greater at the beginning of the season for all N treatments. This suggests on the one hand that the major part of the fertilizer N is leached to deeper soil layers rapidly after fertilization and on the other hand, that a big part of the remaining N of the previous season is carried over the to the following season as inorganic N. This assumption is supported by the high N surpluses in agroecosystems, particularly resulting from plant residues N, in Haean Catchement found at the end of the cropping season by Kettering (2011, in preparation). This also seconds the assumption that no or only little N leaching occurs during the dry and cold winter. Early in the growing season, mean nitrate concentrations of the first three sampling weeks increased among the four N treatments in the order 138 mg NO_3-N l^{-1} (N50) < 140 mg NO_3-N l^{-1} (N150) < 176 mg NO_3-N l^{-1} (N250) < 179 mg NO_3-N l^{-1} (N350), while the mean concentrations of the final three sampling weeks increased in the order 6 mg NO_3-N l^{-1} (N50) < 5 mg NO_3-N l^{-1} (N150) < 53 mg NO_3-N l^{-1} (N250) < 64 mg NO_3-N l^{-1} (N350). These results show that the nitrate concentrations differ more substantial between the different N application rates at the end of the season than in the beginning. This leaching pattern is similar to that observed by Hergert (1986), who showed increased concentrations that were attributed to breakthrough of N from the previous year. The declining in nitrate concentrations in seepage for all four N treatments observed at the end of the season when the heaviest rainfall events occurred is indicative that the major part of the fertilizer N percolated down the soil profile before harvest. Additionally, the ridges show higher NO_3–N concentrations in general but the difference in soil depth seems to be more relevant.

We found that the seasonal mean nitrate concentrations for the four fertilizer N treatments (53 < 67 < 119 < 122 mg NO_3-N l^{-1}) lie all above the regulatory standard of 50 mg NO_3-N l^{-1} from the European Union's Drinking Water Directive (EC 2008). However, combining these result, we found the highest recovery of tracer at the rate N50 (47%) and the rate N150 (39%). A comparable biomass production as the highest fertilizer application rates with a still notably higher recovery of tracer and fairly lower nitrate concentrations in seepage over the cropping season shows rate N150.

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