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ORIGINAL ARTICLE

Fate of fertilizer ^{15}N in intensive ridge cultivation with plastic mulching under a monsoon climate

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Abstract Reducing nitrogen (N) leaching to groundwater requires an improved understanding of the effect of microtopography on N fate. Because of the heterogeneity between positions, ridge tilled fields, frequently used in intensive agriculture, should be treated as two distinct management units. In this study, we measured N dynamics in plastic-mulched ridges and bare furrows with the goal of developing more sustainable agricultural practices with optimal gains, namely crop production versus limited impacts on water quality. We investigated: (1) biomass production; (2) crop N uptake; (3) N retention in soil; and (4) N leaching using ^{15}N fertilizer in a radish crop. Broadcast mineral N fertilizer application prior to planting resulted in high total leaching losses (of up to 390 N kg ha^{-1}). The application of plastic mulch in combination with local fertilizer management did not help to reduce N leaching. At all fertilizer N rates, the mean NO_3^- concentrations in seepage water were found to be above the WHO drinking water standard of 50 mg NO_3^- l^{-1}. To reduce NO_3^- leaching, we recommend: (1) decreasing the fertilizer N rates to a maximum of 150 kg N ha^{-1}; (2) applying fertilizer N in 3–4 split applications according to the plant's N needs; (3) applying fertilizer N to the ridges (after their formation) to avoid losses from the furrows; and (4) increasing the soil organic matter content to enhance the water and nutrient retention by covering the furrows with plant residues.

Keywords N leaching · N retention · Sandy soils · N use efficiency · Stable isotope · Suction lysimeter · Intensive crop management · Spatial heterogeneity

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Introduction

NO_3^- leaching from agricultural fields is considered a major source of water pollution (Buczko et al. 2010; Zotarelli et al. 2007) and high NO_3^-losses occur, especially in intensively cultivated areas with high precipitation and coarse-textured soils. NO_3^- leaching depends on the amount of water percolating through the soil and the NO_3^- concentration in the seepage water (Sieling and Kage 2006), which is strongly influenced by local factors such as climate (arid < humid), soil type (fine-textured soil < coarse-textured soil), and land use system (natural system < agricultural system) (Boumans et al. 2005; Di and Cameron 2002). NO_3^- leaching is difficult to control because it is often derived from large areas of land and losses mostly occur intermittently with rainfall events (Barton and Colmer 2004). NO_3^- leaching processes have been measured using different methods in various crop systems and pastures that had a relatively homogenous spatial distribution of water and NO_3^- (Di and Cameron 2002; Nyamangara et al. 2003; Zotarelli et al. 2007). A factor that complicates the measurement and the interpretation of NO_3^- leaching, however, is that soil structure might induce preferential flow, which is characterized as an uneven and often rapid flow of water and solutes through soil via preferred pathways with the result that only a small part of the soil contributes to most of the flow.

Polyethylene (PE) mulch has been used to cover soil surfaces in South Korea for ridge cultivation of vegetable crops (Fig. 1). When this method is practiced, the ridges are covered with a plastic film, but the furrows are left uncovered, which should diminish NO_3^- leaching (Henriksen et al. 2006; Islam et al. 1994; Romic et al. 2003). However, the soil surface microtopography associated with this practice results in a non-uniform distribution of water and N. Previous studies focused on comparing total N leaching amounts between flat tillage, ridge cultivation, and/or ridge cultivation with plastic mulching (Drury et al. 1993; Romic et al. 2003; Vázquez et al. 2005). The potential differences in N fate between plastic-mulched ridges and bare furrows in dryland agriculture have not been extensively evaluated. Many processes, such as water flow and solute transport, are different in the ridge and furrow zones. Additionally, this microrelief might even increase the total leaching as both sites are interrelated, and the water volume in furrows increases in the presence of ridges (Leistra and Boesten 2008). The PE mulch protects the ridges from direct infiltration, and hence, the fertilizer N beneath the ridge is protected against percolation with seepage water. It consequently intensifies percolation in the furrows (Bargar et al.1999; Henriksen et al. 2006; Islam et al. 1994), which in turn can lead to water ponding on the furrow surface after heavy rainfall. However, due to the lower fertilizer N concentrations in the furrows, the total amount of NO_3^- leaching is assumed to decrease. Consequently, N retention in ridge soil and N uptake by plants is expected to increase.

In the mountainous highlands of Gangwon Province in South Korea, the agricultural systems have shifted over the last 40 years towards intensive management that depends heavily on high mineral N fertilizer inputs. Recommendations for highland summer radishes provided by the Rural Development Administration of South Korea (RDA) amounted to 252 kg N ha^{-1} (RDA 2006), although local farmers have adopted N application rates of up to 400 kg N ha^{-1}.

Due to the high soil erosion loss from mountainous cropland areas, local farmers use a management practice of frequently adding sandy soil to the top layer of agricultural fields to compensate for soil loss. Excessive N fertilization and the predominantly sandy soils, together with heavy summer monsoon rainfalls, result in high N losses, which lead to surface and groundwater pollution in many of the thousands of small agricultural watersheds in South Korea. Our study site, Haean Catchment, is a subcatchment of the Lake Soyang watershed, which is a major drinking water reservoir in South Korea and is known as a hot spot of agricultural non-point source pollution (Jung et al. 2009; Kim et al. 2006). It is a typical basin with characteristics representative of South Korean agricultural areas such as the following: (1) high N inputs exceeding crop demands; (2) cultivation on sandy soils; (3) dependence on monsoon rainfall; (4) a high proportion of vegetable production; and (5) specific management practices such as ridge cultivation with black PE mulch.

The purpose of this study was to quantify the N dynamics for plastic-mulched ridges and bare furrows with the goal of developing more sustainable agricultural practices to reduce non-point source pollution of water resources. Using ^{15}N, we investigated the fertilizer N budget, including the following: (1) N uptake by crops; (2) N retention in soil; and (3) downward movement of N with percolation in a radish (*Raphanus sativus L.*) production system under conventional local management. The use of ^{15}N isotopes are invaluable for tracing the fate of fertilizer N in soil/plant systems (Xu et al. 2008) because ^{15}N undergoes the same chemical and microbial transformations as ^{14}N in the soil. Hence, analysis of the ^{15}N content in plant parts and soil was evaluated at selected times during the growing season, and ^{15}N content was used as a measure of the actual ^{15}N recovery and ^{15}N loss

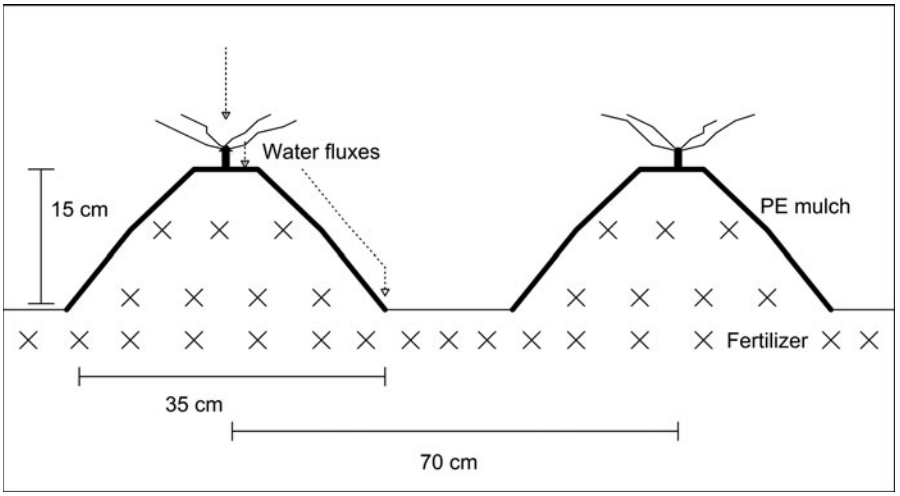

Fig. 1 Scheme of a typical ridge cultivation system with plastic mulching used for radish production in a temperate South Korean area with summer monsoonal climate. The water fluxes (*arrow*) and the distribution of fertilizer N (X) in the system are indicated

derived from the fertilizer (Buresh et al. 1982; Vlek and Byrnes 1986). To evaluate the effect of plastic-mulched ridges on NO_3^- leaching, a two-dimensional process-based modeling study was carried out using the numerical model Hydrus 2/3D. To assess productivity implications versus environmental impacts of N fertilizer use: namely impacts on water quality, N dynamics were examined at fertilizer N application rates from 50 to 350 kg N ha^{-1} on top of the basal fertilization rate of 56 kg N ha^{-1}. Because N leaching was absent during the dry and cold winter, we conducted the field and the modeling study only during the growing season.

Materials and methods

Study site

The field experiment was conducted on a typical Korean terric cambisol also considered an anthrosol (IUSS Working Group WRB 2007) (Table 1) because of the artificial long-term addition of sandy soil on to the top of the fields at the Punchball Tongil Agricultural Experimental Farm (38.3°N, 128.14°E, 420 m asl) in the Haean-myun Catchment in Yanggu County, Gangwon Province, South Korea. The experiment went from June 1 to August 28, 2010.

Daily precipitation and temperature data were monitored with an automatic weather station (WS-GP1, Delta-T Devices, Cambridge, UK) at the site and compared with meteorological data for the Haean Catchment (own data) (Fig. 2). The study area falls within the East-Asian monsoon climate and has an 11-year (1999–2009) average annual air temperature of 8.5 °C and an annual precipitation of approximately 1577 mm. For March, April and May, the temperature was colder than the 11-year mean (Fig. 2a). This led to a delay in the start of cropping by approximately 2–4 weeks. However, 70 % of the total precipitation occurs as heavy rainfall between June and August. In recent decades, a shortening of the monsoon season was observed, as well as an increase in the amount of precipitation, and the number of heavy rainfall days (Chung et al. 2004). Rainfall events for the experimental period (2010) were comparatively low however, with a maximum daily precipitation of less than 70 mm. The months of June and July in 2010 had precipitation amounts of only 67 and 216 mm, respectively, which were exceptionally low compared to the 11-year averages. Very dry periods, each with less than 20 mm precipitation in total, were observed from June 14 to July 1, July 6 to July 15, and from July 19 to August 1. In contrast, the months of August and September were extremely wet, with precipitation amounts of 458 and 415 mm, respectively (Fig. 2b). The heaviest rainfall during the experiment was 150 mm in the 3 days from August 13 to 16. Although no runoff was observed throughout the experimental period, water sometimes ponded on the furrow surface after a heavy rainfall.

Experimental design

Before the experiment started, a commonly used granular fertilizer (30 % mineral NPK fertilizer, 4.2–2–2; 70 % organic fertilizer, SamboUbi, South Korea)

Table 1 The sand, silt and clay (%) contents, texture and bulk density (d_B) of the soil at the experimental field site in the Haean Catchment in 2010

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture[a]	d_B (g cm^{-3})
0–20	81 (±*0.8*)	16 (±*0.7*)	3.0 (±*0.2*)	Loamy sand	1.48 (±*0.07*)
20–40	77 (±*1.5*)	19 (±*1.2*)	3.6 (±*0.3*)	Loamy sand	1.48 (±*0.06*)
40 − 60	73 (±*1.5*)	22 (±*1.2*)	4.4 (±*0.4*)	Sandy loam	1.54 (±*0.01*)

The soil sampling was carried out before the creation of the ridges

The standard error of the mean is given in italics in parentheses

[a] Soil texture taken from the IUSS Working Group (2007)

was applied at the rate of 56 kg NO_3^-–N ha^{-1} on May 31, 2010, and mixed in the top 0.15 m of the soil to enhance soil fertility of the previously fallow field. On June 1, NO_3^-–N was applied as a one-time top dressing (mineral NPK fertilizer, 11–8–9 +3MgO + 0.3B, KG Chemicals, South Korea) at four fertilizer N rates: N50, N150, N250, and N350, reflecting the application of 50, 150, 250, and 350 kg NO_3^-–N ha^{-1}. The N250 treatment satisfied the recommendations for highland radishes provided by the RDA (2006). Each treatment was applied to a plot (7 × 7 m) and replicated three times at the field site. A randomized block design was used for the experimental layout. On June 9, the top 0.2 m of the soil was ploughed, and the ridge system (35 cm wide and 10–15 cm high) was implemented with a distance of 70 cm between the rows (Fig. 1). The ^{15}N labeling experiment was performed in microplots (125 × 75 cm), each containing one bare furrow and one ridge with six labeled radish plants. Each plot included three microplots, one for each sampling day (day 25, 50, and 75). $K^{15}NO_3^-$ (10 at%) was applied as a tracer to the microplots on June 10. After application of the tracer, the ridges were covered with impervious black PE mulch on June 11. Finally, radishes were sown on the top of the ridges on June 14 (Day 0) at a plant density of 25 cm (Hungnong Seeds, South Korea). Weeding during the experiment was performed manually without the application of herbicides. The plots were harvested after 75 days of growth on August 28.

Study of soil water dynamics

To estimate NO_3^- loss in seepage water, suction lysimeters combined with a soil hydrological monitoring network of standard tensiometers were installed. The suction lysimeters consisted of a

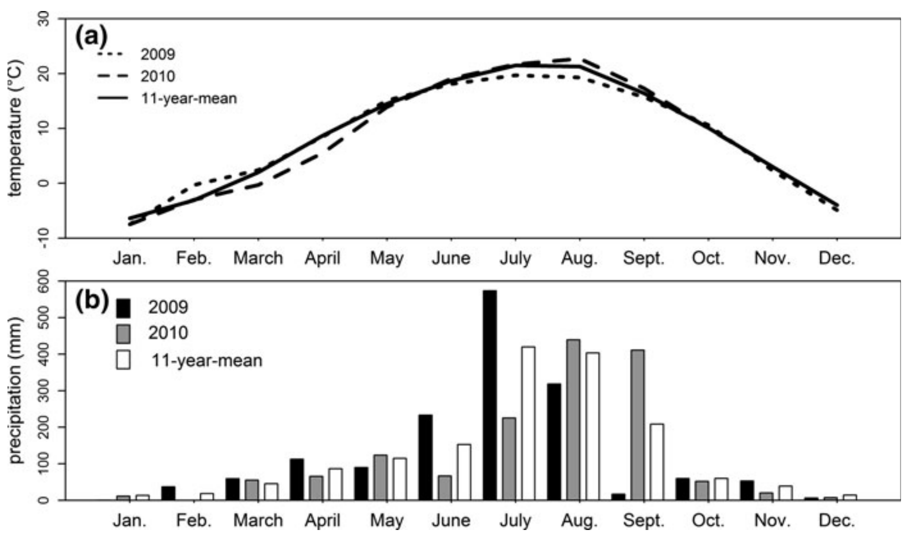

Fig. 2 **a** Mean daily temperature (°C) and **b** mean total precipitation (mm) for the years 2009 and 2010 as well as the 11-year mean (1999–2009) for the Haean Catchment

ceramic cup, a PVC tube, and a PE suction tube. The latter was connected to samplers (brown glass bottles), which were connected through a network of high-density tubing to a vacuum pump (KNF Neuberger, Type N86KNDCB 12v, Freiburg i.Br., Germany). In each microplot, two suction lysimeters were placed in the ridge (15 and 45 cm from the top of the ridge), and one was placed in the furrow (45 cm from the top of the ridge). The suction lysimeters were installed by following the recommendations of DGFZ and HLUG (2004) and UMS (2008). Quantifying N losses associated with downward percolation is highly challenging due to uncertainties associated with estimating drainage fluxes and solute concentrations in the seepage (van der Laan et al. 2010). Suction lysimeters can be used to determine the NO_3^- concentrations in seepage but provide no information on water fluxes. Hence, a process-based numerical model was used for the inverse simulation of water flow and the estimation of NO_3^- leaching (Hydrus 2/3D, Simunek 2006). The ability to represent physical processes such as subsurface water flow in variably saturated media is an advantage of process-based numerical models. Uniform flow processes in a variably saturated porous media without preferential flow pathways can be described using the extended Richards' equation based on the Galerkin linear finite element method. The extended Richards' equation for water flow incorporates a sink term, which considers water uptake by roots. We used the data defined for sugar beet from the Hydrus 2/3D data base because radish data was not available. Surface boundary conditions were set to atmospheric conditions in furrows and planting holes, whereas plastic-mulched areas were set to no flux conditions. Soil evaporation and crop transpiration were calculated with the FAO-56 dual crop coefficient approach using weather parameters such as solar radiation, air temperature, wind speed, humidity and air pressure, which were measured by the weather station at the experiment site. The amount of precipitation was multiplied by 2 to include the surface runoff from the plastic-mulched ridges to the furrows (Dusek et al. 2010). The Van Genuchten parameters, the saturated and the residual water content θs & θr, α & n, and the saturated hydraulic conductivity (K_{sat}) were initially estimated based on texture and bulk density using the Rosetta lite DLL module, which is implemented in Hydrus 2/3D, for each microplot individually. The optimization of the Van Genuchten parameters was performed based on the Levenberg–Marquardt algorithm using the measured pressure head values in the field, which is a parameter estimation technique for inverse estimation of selected soil hydraulic and/or solute transport and reaction parameters from measured data.

Hydrus 2/3D numerically solves Fickian-based advection–dispersion equations for solute transport in variably saturated porous media using the Galerkin linear finite element method. To solve the advection–dispersion equations, water content and volumetric flow need to be defined. Therefore, Hydrus 2/3D first solves the Richards' equation and subsequently simulates the solute transport. To adjust the simulation of the solute transport to the measured NO_3^- concentrations in the seepage water, the solute reaction parameters longitudinal dispersion D_L and denitrification rate k were inverse optimized. Because Hydrus 2/3D is not able to inverse simulate several solutes at the same time, the simulation was kept fairly simple and was carried out only for NO_3^-. Other N forms were therefore not included in the simulation. N uptake by crops takes place passively in the simulation and is linked to crop water uptake. The NO_3^- concentration at the start of the simulation was calculated from the N application rates N50, N150, N250, and N350 and defined up to the soil depth of 24 cm. This soil depth was calculated based on the assumption that the fertilizer was uniformly mixed into the upper 15 cm of the soil with ploughing. With the creation of the ridges, however, the fertilizer was distributed from the top of the ridge down to 24 cm soil depth. The NO_3^- concentrations for all fertilizer rates were subsequently calculated taking the specific soil volume and its water content into account. For the solute transport simulation, we assumed that a) all applied fertilizer N was applied as NO_3^-, b) N mineralization, N fixation, and atmospheric N deposition during the 75 days of growth were negligible, and c) the N fertilizer granules all dissolved immediately in the soil water. Denitrification, however, was included in the simulation because the soil in a depth of 50 cm and deeper was often saturated and anaerobic conditions were assumed. Denitrification was the only unmeasured sink term for NO_3^- in soil and was inverse simulated as a first order kinetic process. The simulation of water flow as well as solute transport was carried out for one of the three replicates of each N application rate.

The simulation of water flow was carried out for 74 days and started at the time of planting at June 14, 2010 (day 0). The simulation of the NO_3^- transport, however, was carried out for 78 days and started at June 10, 2010. Different statistical techniques such as Pearson's correlation coefficient (R), the coefficient of determination (R) and Nash–Sutcliffe efficiency (NSE) were used to evaluate the models. The water flow models achieved a good agreement between measured and simulated pressure heads (Table 2). To examine the influence of differing Van Genuchten parameters or differing saturated hydraulic conductivities on the amount of percolated water, we tested the simulations with two methods (Monte Carlo simulation with random combinations of the parameters and gradually modified parameters). The sensitivity analysis showed that the water fluxes were robust against changes in hydraulic parameters.

The inverse simulation of NO_3^- transport, however, showed a weaker agreement between the measured and the simulated NO_3^- concentrations in seepage water (Table 3), underestimating the NO_3^- concentrations for the fertilizer application rates N50, N250, and N350 and overestimating those for the N150 fertilizer rate.

Sampling and analysis

Above-ground and below-ground biomass was measured gravimetrically in each microplot at day 25, 50, and 75 after sowing. Four ^{15}N labeled plants in each plot were harvested to determine the fresh weight (FW) and dry weight (DM) of shoots and roots (Wu et al. 2012) and to analyze ^{15}N excess (at%). Immediately after separation of the plant parts, the FW was measured, and DM was determined after drying at 70 °C for at least 48 h. An aliquot of each plant part was ground (<0.25 mm) with a ball mill (Brinkman Retsch, MM2 Pulverizer Mixer Mill, Germany) for isotopic analysis and stored until further analysis. Soil samples (ridge: 0–20, 20–40, 40–60 cm, furrow: 15–40, 40–60) with three replicates each were collected at day 25, 50, and 75 after sowing with a soil corer (diameter: 5 cm). Soil sampling and analysis were conducted separately for ridges and furrows. The soil samples were dried at 60 ° C, mixed, and sieved (<2 mm). An aliquot of each soil sample was ground (<0.25 mm) with a ball mill (Brinkman Retsch, MM2 Pulverizer Mixer Mill, Germany) for isotopic analysis and stored until further analysis. Total N content and ^{15}N in soil and plant samples were determined using an elemental analyzer (NC 2500, CE Instruments, Italy) coupled with an isotope mass spectrometer (delta plus, Thermo Fisher Scientific, Germany) through a ConFlo III open split interface (Thermo Fisher Scientific, Germany) as further specified in Bidartondo et al. (2004). To determine N loss through seepage water, the soil water samplers at each depth (15, 45 cm) and position (ridge, furrow) were separately sampled for chemical analysis approximately on a weekly basis (30.06.2010, 05.07.2010, 10.07.2010, 22.07.2010, 29.07.2010, 04.08.2010, 14.08.2010, 23.08.2010). Samples were refrigerated at 5 °C within 2 h of collection and analyzed within 24 h 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®, MERCK, South Korea) and by using a photometer (LP2W Digital Photometer, Dr. Lange, Germany).

^{15}N calculations and tracer recovery

^{15}N concentration in dry plant and soil material ($^{15}N/^{14}N$ at%) was corrected for natural ^{15}N abundance

Table 2 Comparison of the model evaluation coefficients R^2, R, NSE, and STDV for the simulations of soil water dynamics of the four fertilizer N application rates N50, N150, N250, and N350 using Hydrus 2/3D

Fertilizer N application rate	R^2	R	NSE	STDV
N50	0.6366	0.7979	0.6026	7.4884
N150	0.6483	0.8052	0.5216	10.833
N250	0.7385	0.8594	0.6122	8.8381
N350	0.6654	0.8157	0.6325	11.436

R^2 coefficient of determination, *R* Pearson's correlation coefficient, *NSE* Nash–Sutcliffe efficiency, *STDV* standard deviation of the mean

Table 3 Comparison of the model evaluation coefficients R^2, R, NSE, and STDV for the simulations of the NO_3^- transport of the four fertilizer N application rates N50, N150, N250, and N350 using Hydrus 2/3D

Fertilizer N application rate	R^2	R	NSE	STDV
N50	0.3174	0.5634	0.2451	3.13×10^{-5}
N150	0.5033	0.7094	0.3927	-1.42×10^{-5}
N250	0.3508	0.5923	−0.0340	4.69×10^{-5}
N350	0.1354	0.3680	−0.1817	0.61×10^{-5}

R^2 coefficient of determination, *R* Pearson's correlation coefficient, *NSE* Nash–Sutcliffe efficiency, *STDV* standard deviation of the mean

(at%). ^{15}N concentrations were then converted to an area basis (mg ^{15}N m^{-2}) using Eqs. 1, 2 and 3 (Buchmann et al. 1995):

$$[^{15}\mathrm{N}] = {}^{15}\mathrm{N}/{}^{14}\mathrm{Nat}\%/100 * [\mathrm{N}] \quad (1)$$

With [N] = N concentration.

$$\text{Plant samples}: {}^{15}\mathrm{N\,g\,m}^{-2} = [^{15}\mathrm{N}] * \mathrm{bio\,g\,m}^{-2} \quad (2)$$

With bio g m^{-2} = biomass (g) per unit ground area (m^{-2}).

$$\text{Soil samples}: {}^{15}\mathrm{N\,g\,m}^{-2} = [^{15}\mathrm{N}] * d_B * s \quad (3)$$

With d_B = bulk density of each soil layer, s = soil volume of soil horizon in m^3.A ^{15}N budget was calculated for each fertilizer N application rate. The ^{15}N uptake by crops was expressed as the percentage of applied ^{15}N fertilizer taken up by the above- and below-ground plant parts and reflects the fertilizer N use efficiency of the plants. The ^{15}N retention in soil was described as the percentage of applied ^{15}N fertilizer recovered in the top 60 cm of the soil profile. Only the upper 60 cm of the soil was used for the calculations because more than 90 % of the roots were found in the upper 30 cm and N that leached deeper than 60 cm was lost to groundwater. ^{15}N recovery was calculated as the sum of ^{15}N uptake by plants and the ^{15}N retention in soil. The ^{15}N loss was calculated by subtracting the uptake by plants and retention in soil (i.e. recovery) from 100.

Statistical analysis

Statistical analysis was carried out using the statistical software R (version 2.13.2), with a significance level of $P \leq 0.05$. All variables were tested for normal distribution. Mean values are presented in the figures, if not stated differently. Differences in the central location (median) of independent samples (DM, crop N uptake, ^{15}N uptake) were analyzed using the Kruskal–Wallis non-parametric analysis of variance and pairwise comparisons using the Wilcoxon rank sum test with Bonferroni correction. Differences in the central location (median) for dependent samples (seepage NO_3^- concentration, ^{15}N retention) were analyzed using the Friedman non-parametric ANOVA and pairwise comparisons using the Wilcoxon matched pair test.

Results

Plant biomass and ^{15}N uptake in crops

The total DM produced at the final harvest increased with the increase in fertilizer N application rate. Maximum DM was produced under the N350 fertilizer rate (5.5 Mg ha^{-1}), with significantly lower final DM for N50 (4 Mg ha^{-1}). While the DM increased significantly from day 25 to day 50 for all N application rates, it did not increase at any N application rate for the last 25 days of the growth period (Fig. 3a).

The greatest ^{15}N uptake by the crop was observed for the N50 treatment (36 %) at day 50, and was also highest for N150 at this time (Fig. 3b). Crop ^{15}N uptake increased continuously for the entire 75 days of growth only for the higher fertilizer N rates (N250, N350) however. The increase in ^{15}N uptake from day 25 to day 50 was significant for all N application rates. The increase for the last 25 days was only significant for the N350 treatment. The ^{15}N crop uptake reflects the fertilizer N use efficiency of the plants. At the first sampling day (day 25), the order of the mean fertilizer N use efficiency was as follows: 3.8 % (N150); 3.7 % (N50); 2.7 % (N250); 1.7 %

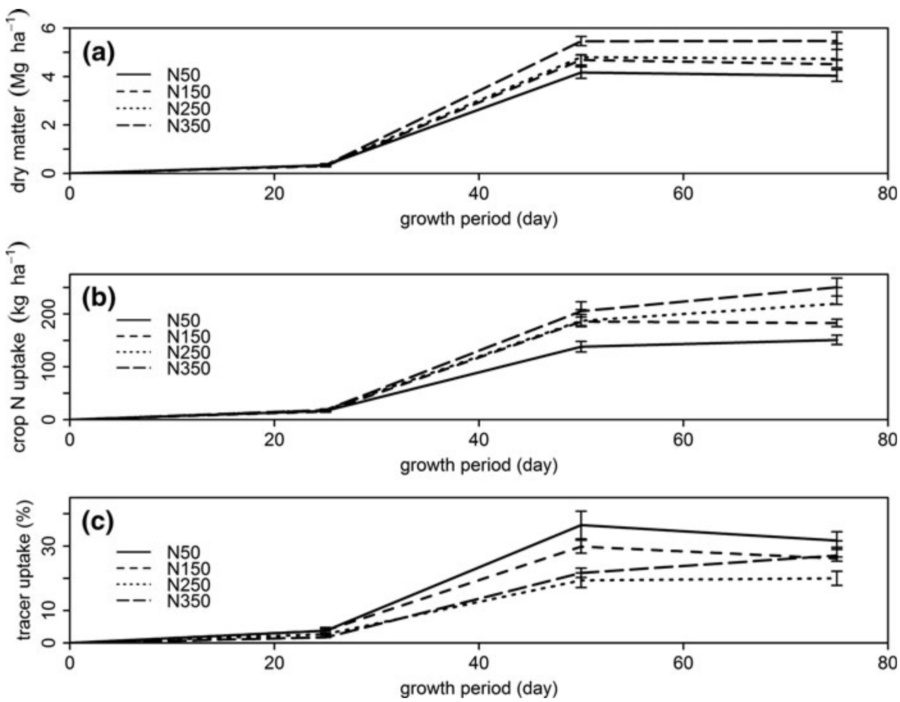

Fig. 3 **a** Mean dry matter production (Mg ha^{-1}), **b** total crop N uptake (kg N ha^{-1}), and **c** ^{15}N uptake by plants (% of ^{15}N applied) at the four fertilizer N rates over 75 days of growth. *Error bars* are standard error of the mean

(N350). At day 75, the total crop ^{15}N uptake ranged between 20 % (N250) and 32 % (N50), and this difference was significant. The mean fertilizer N use efficiency of all fertilizer N rates at final harvest was found to be 27 %.

Total crop N uptake increased linearly with an increase in the fertilizer N application rate by day 75 ($R^2 = 0.97$), while in the first 50 days of the growing period there was no difference between crop N uptake for the N150 and N250 application rates (Fig. 3c). The increase in N uptake by crops was only significant from day 25 to day 50 at all four N application rates. The crop N uptake at the two lower fertilizer N rates (N50, N150) did not change from day 50 to day 75, whereas the uptake continued to increase at the two higher N application rates, leading to the highest final crop N uptake of all four N application rates.

^{15}N retention in soil

The order of the final ^{15}N retention (% of ^{15}N applied), averaged for all sampling depths, was as follows: 14 % (N50); 13 % (N250); 11 % (N150); 10 % (N350), and were not statistically significantly different. Ridges appeared to have retained more soil ^{15}N than furrows but the differences ($P > 0.05$) were not significant (Fig. 4). In the ridge position as well as in the furrow position, the final soil ^{15}N retention decreased with increasing soil depth but the differences were not significantly different ($P > 0.05$) (Table 4).

N content in soil solution and N leaching

The total volume of water added to the simulation consisted of the amount of precipitation and the soil water content at the beginning of the simulation. The amount of water which was discharged in the simulation consisted of the amount of water that percolated deeper than 45 cm and the amount of water that was lost by transpiration and evaporation. The simulated amounts of total seepage water percolating deeper than 45 cm during the 75 days of growth were in the order: 774 l m^{-2} (N350); 796 m^{-2} (N50); 853 m^{-2} (N150); 887 l m^{-2} (N250) based on simulations for one replicate plot per fertilizer N application rate. In the simulation, the furrows contributed 1.5- to 3-times more than the ridges to the total amount of seepage water (Fig. 5). Simulated seepage water fluxes were strongly affected by rainfall and increased considerably with each heavy rainfall event at all N application

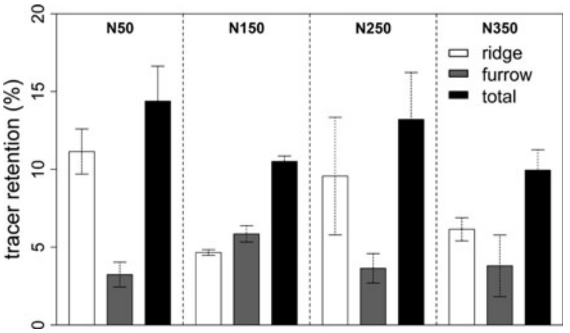

Fig. 4 Mean soil ^{15}N retention (% of ^{15}N applied) averaged for all depths at day 75 of growth. Results are given for ridges and furrows separately and totaled for each of the four fertilizer N rates. *Error bars* are standard error of the mean

rates. Accordingly, the highest seepage water fluxes were simulated on July 16, August 10, and August 13–16, 2010, when the measured precipitation was high, while the dry periods of June 14–30 and July 25 to August 2, 2010 showed low seepage water fluxes.

Mean seasonal NO_3^- concentrations in seepage water increased ($P < 0.05$) with an increase in fertilizer N rate in the following order: 53 mg l^{-1} (N50) < 67 mg l^{-1} (N150) < 119 mg l^{-1} (N250) < 122 mg l^{-1} (N350). This order was common at all sampling depths as well as for ridge positions and furrow positions. Mean NO_3^- concentrations of seepage water for the four fertilizer N rates were similar at the beginning of the experiment (138–179 mg NO_3^- l^{-1}) in contrast to differences ($P < 0.05$) observed at the end of the experiment (5–64 mg NO_3^- l^{-1}).

NO_3^- concentrations in seepage water were not different ($P > 0.05$) at the two sampling depths (15 and 45 cm). The NO_3^- concentrations separately sampled in the ridges and in the furrows at a soil depth of 45 cm, in each case measured from the top of the ridge, also were not significantly different (Fig. 6). The continuous and quick decline in NO_3^- concentrations in seepage water from the N50 and N150 treatments resulted in concentrations less than 10 mg NO_3^- l^{-1} at the end of July (day 45–50 after sowing). In contrast, gradual and discontinuous decreases in NO_3^- concentrations from the N250 and N350 application rates resulted in concentrations greater than 40 mg NO_3^- l^{-1} at the end of July and over 10 mg NO_3^- l^{-1} at the final harvest. The concentration pattern at the beginning of the measurements was unexpected. Although the fertilizer was applied 4 weeks before the first seepage water sampling, the peak concentrations did not occur at the beginning of the seepage water measurements but around day 21 for the ridge position at a depth of 15 cm and around day 28 for the ridge position and furrow position at a depth of 45 cm.

Because ^{15}N in seepage water was not measured to determine the proportion of mineral N fertilizer that leached deeper than the rooting zone, the simulation

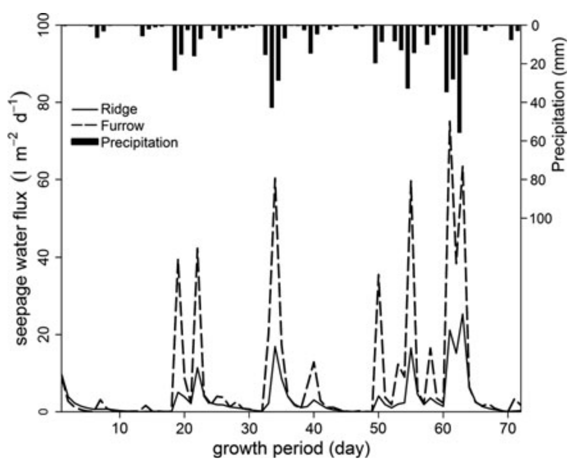

Fig. 5 Mean simulated daily seepage water fluxes (l m^{-2} day^{-1}) in soil at a depth of 45 cm during the 75 day growth of a radish crop. Daily seepage water was simulated for one replicate plot of each of four fertilizer N application rate treatments

Table 4 Soil ^{15}N retention (% of ^{15}N applied) at different sampling depths in the ridges and the furrows at day 75 of the experiment. The standard error of the mean is given in italics in the parentheses

N application rate	Ridge			Furrow	
	0–20 cm	20–40 cm	40–60 cm	15–40 cm	40–60 cm
N50	9.19 (*0.84*)	6.81 (*0.75*)	3.67 (*1.00*)	2.71 (*0.63*)	0.53 (*0.11*)
N150	3.7 (*0.25*)	0.96 (*0.95*)	0.51 (*0.16*)	4.70 (*0.15*)	1.15 (*0.43*)
N250	8.29 (*2.82*)	1.28 (*0.68*)	0.97 (*0.27*)	3.12 (*0.55*)	0.52 (*0.12*)
N350	5.03 (*0.54*)	1.12 (0.86)	0.57 (*0.10*)	3.18 (*1.26*)	0.63 (*0.14*)

results from each replicate plot per fertilizer rate were used. The simulated total quantity of NO_3^- that leached deeper than 45 cm during the growing season increased linearly ($R^2 = 0.99$) with an increase in fertilizer N rate: 86 kg NO_3^- ha^{-1} (N50) < 180 kg NO_3^- ha^{-1} (N150) < 260 kg NO_3^- ha^{-1} (N250) < 387 kg NO_3^- ha^{-1} (N350) (Fig. 7). Additionally, the simulated NO_3^- leached was strongly affected by rainfall amounts with leached NO_3^- increasing considerably on days with high precipitation, while on days with low or no precipitation daily leached NO_3^- decreased and was fairly low. Accordingly, the peaks of high daily NO_3^- leaching were all found on days with high precipitation. The pattern of the daily NO_3^- leaching was therefore highly consistent with the pattern of the seepage water fluxes. The ridges and furrows, however, contributed equally to the total amount of leached NO_3^- at all fertilizer N application rates.

Discussion

Plant biomass and ^{15}N uptake by crops

The results for DM production were supported by earlier findings that showed that the highest biomass production for radishes was recorded at the highest rates of fertilizer N (Guvenc 2002). However, the lack of significant differences in DM production between N150, N250 and N350 indicates that similar crop yields can be achieved with lower fertilizer N rates. In contrast, a significantly lower DM production was observed at N50 when compared to the higher N application rates, which implies that an N fertilizer rate of 150 kg N ha^{-1} is adequate to achieve maximum biomass production.

The maximum ^{15}N uptake by plants by day 50 in the N50 and N150 treatments suggest that most of the fertilizer N was either taken up by crops or lost from the soil by day 50 with only minor amounts of ^{15}N subsequently taken up by the crops in the remaining 25 days. This was highly consistent with the fact that no significantly greater biomass production was observed in the last 25 days of growth for any of the four N application rates. Furthermore, previous research has shown that the total N content of the plants increased with an increase in the N application rate, as did the NO_3^- content of the radish (root) (Guvenc 2002). According to Guvenc (2002), N taken up after day 50 accumulated mostly in the root, rather than being used for further growth. The final mean fertilizer N use efficiency of all 4 N application rates was as low as 27 %. ^{15}N isotopes are an invaluable tool to estimate fertilizer N use efficiency. Studies with ^{15}N fertilizers have often shown that fertilizer ^{15}N application increased plant uptake of unlabeled soil N due to mineralization-immobilization turnover (Jenkinson et al. 1985; Kuzyakov et al. 2000). Hence, for soils low in native N, ^{15}N uptake by crops may decrease if immobilization of fertilizer ^{15}N occurs to a significant extent. This pool substitution could lead to an underestimation of the fertilizer ^{15}N uptake by plants (Eviner et al. 2000; Vlek and Byrnes 1986) and the low fertilizer N use efficiencies recorded in this study.

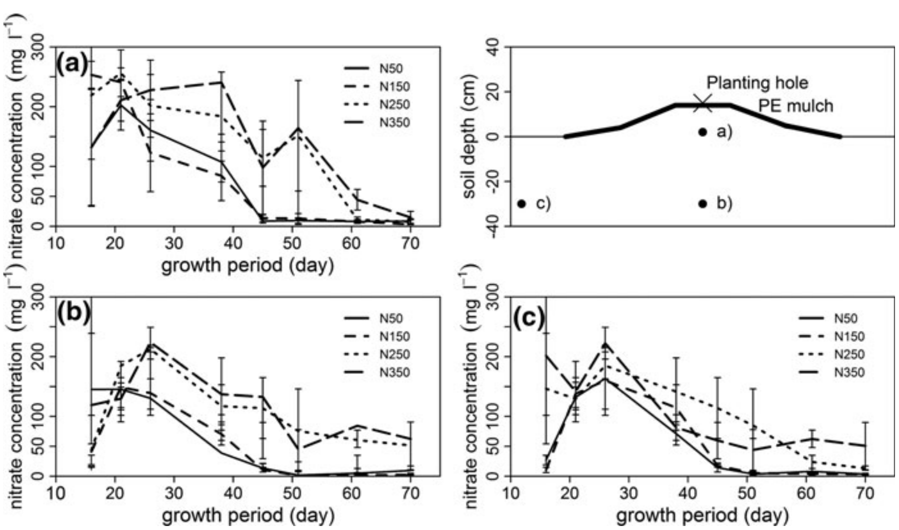

Fig. 6 Mean (n = 3) nitrate concentrations in seepage water (mg l^{-1}) at ridge and furrow positions and two soil depths (15, 45 cm) for the four fertilizer N rates. **a** ridge at a 15 cm depth; **b** ridge at a 45 cm depth; **c** furrow at a 45 cm depth. The graphic *top right* shows the location of the suction lysimeters for collecting seepage water. *Error bars* are standard error of the mean

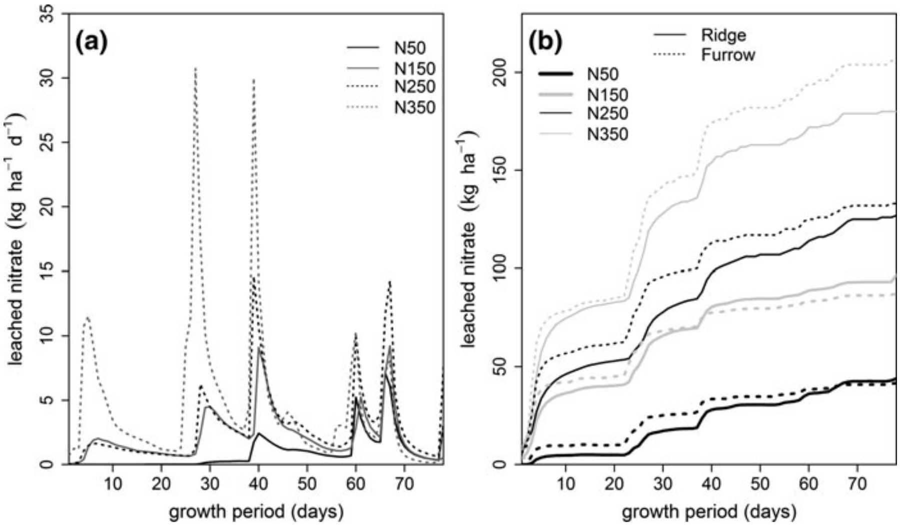

Fig. 7 **a** Simulated daily leached NO_3^- (kg N ha^{-1} day^{-1}) for the four fertilizer N rates and **b** simulated cumulative leached NO_3^- (kg N ha^{-1}) for the four fertilizer N rates and for ridges and furrows separately during the radish growth period of 75 days. Daily leached nitrate was simulated for one replicate plot of each fertilizer N application rate only

Taking this underestimation into account, although the effect was probably of secondary importance for the sandy soils of the experimental field, the calculated mean fertilizer N use efficiency was still fairly low compared to the 44 % fertilizer ^{15}N recovery observed in cereals (Dobermann 2005).

The low fertilizer N use efficiency of <4 % in the first third of the growing season contributed to the overall low N use efficiency. Although most N was taken up at the beginning of the growing season, the crop was unable to utilize all available N, and hence, the excess fertilizer N applied at the beginning of the growing season had a high potential of being lost to the groundwater in the sandy soils.

N retention and N content in seepage

Sandy soils with their low water and nutrient retention capacity are extremely susceptible to the rainfall events occurring early in the season, especially when the crops have not yet emerged. Percolation risk increases with increasing precipitation at the beginning of the monsoon season, which usually starts at the end of June in South Korea. Although precipitation was exceptionally low in June 2010, a rainfall event with 42 mm of precipitation occurred shortly after the tracer application. The coarse texture of the upper 60 cm of the homogenous sandy soils and their poor sorption characteristics increased the risk of ^{15}N percolating quickly to deeper layers instead of accumulating in the soil (Shrestha et al. 2010), with no difference in final ^{15}N retention in soil between the four N application rates or at either sampling depth. The low final ^{15}N retention in soil was consistent with that of other disturbed ecosystems (Peterjohn and Correll 1984). A higher ^{15}N retention was expected in the covered ridges compared to the bare furrows based on the procedure used for fertilizer application. While the fertilizer was uniformly distributed in the field when applied, most of the fertilizer N would have accumulated on the ridges during their creation. In addition, the ridges were covered with plastic mulch, which was assumed to protect the soil from direct infiltration of excessive precipitation and accordingly was expected to reduce the possibility of N leaching losses (Leistra and Boesten 2010; Romic et al. 2003). However, ^{15}N retention was similar in the ridges and the furrows at all N application rates at the final harvest. This unexpected behavior was most likely due to the ^{15}N uptake by crops in the ridges compared to the absence of crops preventing ^{15}N uptake in the furrows. Besides the primary radish root, the spreading root system of radishes is only weakly developed dominated by short fine roots. These conditions also imply that the fertilizer, which is distributed in the furrows, is most likely in excess to that required and irreversibly lost from root water uptake. Another potential reason might be stemflow of precipitation water through the canopy leading to local infiltration and preferential flow in the ridge soil, which was observed in other field studies (Leistra and Boesten 2010; Saffigna et al. 1976).

This might reverse the protective effect of the PE cover. A modeling study on water flow in ridges and furrows in South Korean agriculture found an additional explanation. Pressure head gradients during dry periods were found to deviate horizontally, indicating a lateral flow direction from the furrows to the ridges. However, during monsoon events, the dominating flow directions were less pronounced because ridges were also fully saturated due to the high hydraulic conductivity of the soils and the consequent quick distribution of soil water from the furrows to the ridges. This high hydraulic conductivity of the sandy soils led subsequently to a quick percolation of the soil water and fertilizer N to deeper soil layers also in the ridges (Ruidisch et al. 2012, in press). This study also implied that there is no protective function of the PE mulch during heavy rain events or during drier periods due to subsurface flows. We hypothesized that seepage water NO_3^- concentrations would be highest at the time of the first seepage water measurements which occurred 3 weeks after the tracer was applied and 4 weeks after the fertilizer was applied. The highest NO_3^- concentrations, however, were found a couple of weeks after the first seepage water sampling (during the first 25–35 days of growth for all four N addition rates). This result might be explained by the fact that the fertilizer N did not dissolve in the soil water immediately and therefore was not immediately susceptible for percolation but at a later point in time. There were no differences in NO_3^- concentration in seepage water between the furrows and ridges implying that the plastic mulch covering the ridges, did not protect them from NO_3^- leaching losses as we would have expected due to the assumed protection of the soil from direct infiltration of excessive precipitation. The similarity in ridge and furrow seepage water NO_3^- is however, highly consistent with the results for the ^{15}N retention in soil from the ridges and furrows and might also be a result of the lateral water fluxes and the mixing of water under furrows and ridges just 1–2 decimeters below the surface. Additionally, NO_3^- leaching is highest for the heavy rain events occuring early in the cropping season and N contents in soils are subsequently low after a few heavy rain events and do therefore not strongly influence NO_3^- concentrations in seepage water. Moreover, the PE mulch did not seem to influence the seepage water NO_3^- concentrations at all because the patterns of the NO_3^- concentrations over the season were identical for the ridges and the furrows. However, the decline in NO_3^- concentrations in seepage water for the smaller rates N50 and N150 was different in its pattern and in its amount from that of the larger rates N250 and N350, supporting the assumption that most of the fertilizer N for the N50 and N150 treatments was either taken up by the crop or lost from the soil by day 50. In this experiment seepage water was only collected weekly. The effect of single rain events on NO_3 concentration in seepage water, such as the rain event shortly after the tracer application, could therefore not be captured experimentally. Despite these limitations, we found that the seasonal mean NO_3 concentrations in seepage water did not meet the WHO water quality standards of 50 mg NO_3 l^{-1} for any of the fertilizer N rates (WHO 2011). This is even more remarkable as the nitrate concentrations of the seepage water were stronlgy diluted by the substantial rainfall.

Seepage water fluxes and total leached N

Simulated seepage water fluxes were highly affected by heavy rain events and increased at days with high rainfall amounts. The furrows contributed more to the total seepage water than the ridges at all four N application rates, because the amount of precipitation in the furrows was multiplied by 2 to include the surface runoff from the plastic-mulched ridges to the furrows. This process of doubling precipitation amount in the furrows might lead to an overestimation of rainfall in the furrows but this procedure was successfully used in other modeling studies (Dusek et al. 2010) and also showed the best agreement between measured and simulated pressure heads in our modeling study. Additionally, several studies proved experimentally that infiltration and initial water movement occurred largely in the furrows mainly due to surface runoff (Bargar et al. 1999; Hamlett et al. 1990; Leistra and Boesten 2010). Li et al. (2000) compared runoff from bare ridges to runoff from plastic-mulched ridges, with the latter showing an average runoff efficiency (runoff/rainfall) of 87 %, with the maximum efficiency being close to 100 %. Additionally, the plastic-mulched ridges were able to generate runoff even under low intensity of the rainfall. Hamlett et al. (1990) observed ponding of water in the furrows, when rainfall exceeded infiltration capacity, as was also observed in our field study. Additionally, stemflow was found in several studies to considerably alter the distribution of water entering the soil. Studies which measured direct stemflow, found that 20–64 % of the irrigation (Lamm and Manges 2000; Saffigna et al. 1976; Steiner et al. 1983) and 4–66 % of the rainfall (Dolan et al. 2001; Parkin and Codling 1990; Saffigna et al. 1976) on the canopy flowed down the stems. However, stemflow is variable in time, dependent on the crop and its development as well as weather conditions (Leistra and Boesten 2008). Considering the morphology of radish leaves, we assumed that stemflow altered water redistribution after precipitation only negligibly. Stemflow was therefore not measured in this study. Influencing parameters like biomass production and soil texture of the simulated treatment plots were similar. Although the water dynamics were only simulated for one replicate plot per fertilizer N rate, the model showed a good agreement between the measured and the simulated pressure heads. Additionally, the sensitivity analysis showed that the water fluxes were robust against changes in the hydraulic parameters. Therefore the simulations of the water dynamics provided a good foundation for the nitrate transport simulations.

In the analysis of the simulated NO_3^- leaching deeper than 45 cm throughout the growing season, we observed very high values of up to 387 kg NO_3^-–N ha^{-1}. These leaching losses observed for the N350 treatment were extremely high and amounted to up to 95 % of the applied fertilizer N. To interpret these results, one has to consider the application of the basal fertilizer (56 kg NO_3^-–N ha^{-1}), which was applied prior to the start of the experiment. However, the total amounts of leached NO_3^- increased linearly with an increase in the N application rate, while biomass production did not significantly increase with increasing fertilizer N rates. Accordingly, the negative effect on water pollution at N250 and N350 was greater than the positive effects of the higher biomass production, indicating high environmental costs caused by exceeding optimum fertilizer N rates. Rapidly increasing amounts of leached NO_3^- at increasing N application rates for ridge tillage on sandy soils have also been reported in studies conducted in ridge cultivations with uncovered ridges (Errebhi et al. 1998; Shrestha et al. 2010). In this experiment, the ridges were covered with PE mulch but the application of PE mulch to the ridges clearly did not prevent the linear or rapid increase observed in the other studies. In contrast, high NO_3^- leaching losses from the plastic-mulched ridges was observed in our study despite the assumed protection from local infiltration and preferential flow in the ridge soil. Additionally, the contribution of NO_3^- leaching from the ridges and furrows was fairly similar. Previous studies showed that fertilizer N should be placed in the active water and nutrient uptake zone and, hence, away from the furrows (Hatfield et al. 1998; Jaynes and Swan 1999) because all fertilizer N, which was placed in the furrows, had a very high risk of being leached. The contribution to the total amount of leached NO_3^- increased considerably in the ridges and in the furrows during heavy rain events, especially early in the growing season. This again indicated that the PE mulch provided little protection of the ridge soil from NO_3^- leaching. However, the increase in NO_3^- leaching during heavy rain events confirmed that the excess N applied prior to planting had a higher probability of percolating deeper than the root zone with the beginning of the summer monsoon season. The summer monsoonal precipitation over Korea has recently increased due to a greater number of heavy rainfall (≥30 mm day^{-1}) events and an increase in the total summertime precipitation (Ho et al. 2003). This change in rainfall intensity and amount, as well as the high inter-annual variability (Ho et al. 2003) amplifies the NO_3^- leaching problem. However, inverse simulation of NO_3^- transport showed a weaker agreement between the measured and the simulated NO_3^- concentrations in seepage water than the simulation of water flow. Consequently we assume that most NO_3^- was leached during/after the first heavy rain events, and the model failed to simulate this occurrence.

^{15}N budget and simulated budget of fertilizer N

A ^{15}N budget for the top 60 cm soil layer was calculated for each fertilizer N treatment for the 2010 cropping season (Table 5). The ^{15}N loss at the end of the cropping season averaged 63 %. The highest ^{15}N recovery was observed for N50 (47 %), followed by the N150 rate (38 %). When simulated values of leached NO_3^- were expressed in relation to applied fertilizer N (basal fertilizer included), NO_3^-–N losses with leaching amounted to 81, 87, 85 and 95 % for N50, N150, N250, and N350, respectively. Simulated N losses with leaching were therefore approximately 25 % higher than the N losses calculated with the ^{15}N budget. This difference is due to uncertainties in the simulations. The underestimation of plant N uptake in the simulation was for example partly responsible for the overestimation of the NO_3^- leaching losses and was consistently observed in other studies (Doltra and Muňoz 2010). The simulated mean N uptake by crops accounted for approximately 15 % compared to the measured mean N uptake of 27 % in our field study. This underestimation in the simulation arises from the fact that the N uptake is linked to the water uptake by the crops and is assumed to take place passively. An underestimation in crop N uptake leads to higher amounts of mineral N left in the soil, which is subsequently prone to leaching. Another uncertainty factor in the simulation is denitrification, and was assumed to account for 2 % of the nitrate in the simulations. This finding was not consistent with other calculations for South Korea (Bashkin et al. 2002) which were higher than our results. However, the microorganisms, which are responsible for denitrification processes need easily available or decomposable carbon (C_{org}) as an energy source and anaerobic conditions in the soil. The C_{org} content of our experimental field was measured to be very low and anaerobic soil conditions are also not plausible due to the high hydraulic conductivity of the soil and the quick drainage of soil water. Hence, we assume that a low denitrification rate is in this case plausible. Limitations of the approach used in this study include the assumption that instant dissolution of N fertilizer granules occurred in soil water. The measured NO_3^- concentrations in the seepage water indicate that this assumption may not have been appropriate for our study. Additionally, the doubling of the precipitation amount in the furrow soil in our modeling study as well as leaving stemflow out of consideration might have led to an overestimation of rainfall in the furrows. Finally, the simulations were carried out only on one replicate plot and no indication of statistically significant differences could therefore be calculated. However, the simulation in combination with the ^{15}N budget showed that NO_3^- leaching as appears to be the dominant N loss pathway for both the ridge and furrow zones in this ridge cultivation system.

Table 5 Nitrogen budget based on the fate of ^{15}N (%) in the top 60 cm of soil at day 75 of the growth of radish under four fertilizer N rates, 50, 150, 250 and 350 kg N ha^{-1}

^{15}N	N50	N150	N250	N350
Recovered	46.8	39.1	30.2	37.9
Crop ^{15}N uptake	31.7	28.1	20.0	29.1
Soil ^{15}N retention	15.1	11.0	10.2	8.8
Lost	53.2	60.9	69.8	62.1

Conclusions

Excessive application of mineral N fertilizer to ridge cultivation with PE mulch on sandy soils resulted in high NO_3^- leaching losses in ridges and furrows, when fertilizer application was broadcast prior to planting.

Based on the finding that soil ^{15}N retention and NO_3^- concentration in seepage water decreased similarly for ridges and furrows during the entire growing season, we conclude that the PE mulch had no significant effect on ^{15}N retention in soil and on NO_3^- concentration in seepage water and did therefore not effectively protect the fertilizer in the ridges from percolation. Accordingly, the ridges and furrows contributed approximately an equal amount of leached NO_3^- to the total amount. Based on the simulation results, we observed that the risk of NO_3^- leaching during heavy rain events was pronounced in both the furrow and the ridge zones. We therefore conclude that the PE mulch provided little protection for the fertilizer N in the ridges during heavy rainfall. Consequently, the ^{15}N uptake was found to be low at all N application rates. NO_3^-–N leaching amounts were further found to increase linearly with an increase in N addition rate as it is well known for ridge cultivations without PE mulch. The PE mulch therefore did not prevent the linear increase in leaching with an increase in fertilizer N addition. We summarize that without the use of additional measures, the application of PE mulch combined with the local fertilizer application practices did not reduce NO_3^- leaching rates and groundwater pollution in Haean Catchment. At all the fertilizer N rates, mean NO_3^- concentrations in seepage water were found to be above the WHO drinking water standard of 50 mg NO_3 l^{-1}.

To reduce NO_3^- leaching, we recommend the following management strategies in addition to the application of plastic mulch: (1) decreasing the fertilizer N rates to a maximum of 150 kg N ha^{-1}; (2) applying fertilizer N in 3–4 split applications according to the plant's N needs; (3) applying fertilizer N only to the ridges (after their formation) to avoid losses from the furrows; and (4) increasing the soil organic matter content to subsequently enhance water and nutrient retention by covering the furrows with plant residues, i.e., rice straw or soil additives. Splitting the applications helps to protect the fertilizer N against the temporal and quantitative variability of the heavy rainfalls, especially at the beginning of the growing season, when the crop N uptake is small. However, split applications might be impractical or more costly in plastic covered ridge cultivations because mechanical equipment is required to apply fertilizer under the PE mulch. The proposed fertilizer N application rate of 150 kg N ha^{-1} equals a N reduction of 40 % compared to the current recommendation of the RDA. The N application rate N150 resulted in a similar biomass production to those with higher fertilizer N rates, while lower NO_3^- amounts in the radishes and significantly lower NO_3^- leaching losses were observed.

Finally, the reasons for the high NO_3^- leaching losses from covered ridges are not completely understood. Further field studies will have to concentrate more on the processes in the plastic-mulched ridges and the subsequent N fate in those ridges to further adjust the management strategies.

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