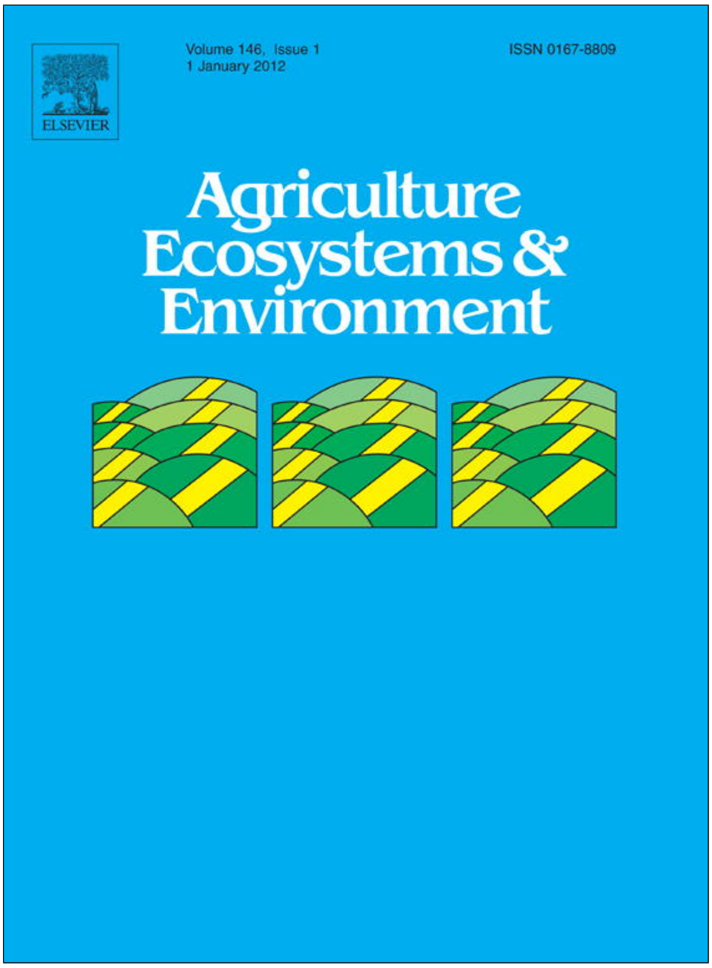
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N fluxes in an agricultural catchment under monsoon climate: A budget approach at different scales

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ABSTRACT

The purpose of this study was to develop options for a more sustainable catchment management, resulting in a reduction of agricultural non-point pollution of water resources in South Korean agricultural catchments. Therefore, an N budget analysis was conducted, which related N inputs into soil under intensive agriculture to N outputs at both field and catchment scale in a mountainous catchment in South Korea. The N budget of all investigated crops was positive, with total N inputs exceeding N outputs by 2.8 times. Radish showed the highest N uptake efficiency (43–45%), whereas rice showed the lowest with 24–30%. At the catchment scale, agriculture contributed over 90% to the maximum N surplus (473 Mg). Rice and radish, with over 100 Mg N surplus each, contributed the largest part. Comparing these results to the N export in the catchment outlet, it was found that N leaching and surface runoff were the dominant loss pathways, leading to a seasonal inorganic N export of 329 Mg. Because fertilizer N was the major N input (>50%) for all crop types except soybean, its reduction was identified as the major scope of action for N savings at the field and catchment scale. The currently observed trend of land use change from annual to perennial crops additionally assists the reduction of N surplus but shows only a spatially limited applicability for the future. Further measures like split applications, application timing to match crop needs and cover crops during the fallow complement the attempt.

1. Introduction

A balanced N cycle in particular in ecosystems intensively managed and modified by humans is necessary as it underpins other ecosystem services, such as crop production and water quality. Crop production and systems with N fertilization above crop needs may result in heavy non-point pollution (Carpenter et al., 1998) of surface and groundwater, severely impacting water bodies (Cherry et al., 2008; Zhang et al., 1996). Non-point pollution refers to pollutants without an obvious point of entry and from large areas. To measure the loading of non-point sources is not easy because the variation of flow and concentration according to the rainfall is very high (Shim and Kim, 2005). Additionally, N losses from agricultural lands represent a monetary and an energy loss to society (Peterjohn and Correll, 1984). Achieving a balance between N inputs and N outputs within an agricultural-based system is critical to ensure short-term productivity together with long-term sustainability (Richter and Roelcke, 2000; Watson et al., 2002). Achieving such a balance is of great importance for agricultural areas in so-called complex terrain. Complex terrain refers to heterogeneous, mostly mountainous, landscapes with irregular topography that represent approximately 20% of the terrestrial surface but provide fresh water to at least half of the humanity worldwide (Liniger et al., 1998). To examine the role of small catchments with differing land use in terms of their contributions of polluted water to a major water reservoir, the N budget methodology can be used.

Nitrogen budgets are an accepted and commonly used tool in environmental studies to relate N inputs in soil to N outputs and have been reviewed by a number of authors (Oenema et al., 2003; Watson et al., 2002; Watson and Atkinson, 1999). A comprehensive overview of the level of difficulties, the limitations and the utility of the most common budget methodologies is provided by Cherry et al. (2008). We used the surface budget methodology but additionally tried to include estimates of N mineralization from soil organic matter (SOM) and soil N_{min} values at the beginning of the growing season. The surface budget methodology does not allow a partitioning between the various N loss pathways, but it still has the potential to illustrate, both qualitatively and quantitatively, the flows into and out of a given system (Watson

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et al., 2002). It provides an assessment of overall N use efficiency and shows when the potential for N surpluses are high. We used two different approaches for the calculation of the surface budgets. While both approaches give the gross N surplus (N input minus crop N) and net N surplus (N input minus harvest N) as a result of the calculations, the total input-approach (TA) calculates the maximum N surplus for the respective field sites and the selected input-approach (SA) respects other N loss pathways than crop N uptake by excluding certain N inputs.

The agricultural systems located in the highlands of Gangwon Province, South Korea, have shifted over the last 40 years towards intensive agriculture that depends heavily on high mineral N fertilizer inputs. Additionally, agriculture is practiced on sandy soils with poor sorption characteristics, and ridge cultivation with polyethylene (PE) mulching is applied. The Rural Development Administration of South Korea (RDA) recommends the following standard fertilizer N application rates for the five investigated key crops: 238 kg N ha^{-1} for highland cabbage, 252 kg N ha^{-1} for highland radish, 137 kg N ha^{-1} for highland potato, 30 kg N ha^{-1} for soybeans, and 90–100 kg N ha^{-1} for paddy rice (RDA, 2006). The average fertilizer N consumption in South Korea, however, was estimated to be 313 kg N ha^{-1} $year^{-1}$ (Kim et al., 2008). Excessive N fertilization and the heavy monsoon rainfalls together with the predominantly sandy soils result in high N losses and lead to surface and groundwater pollution in many agricultural catchments in South Korea. The aim of this study was to develop options for a more sustainable catchment management, resulting in a subsequent reduction of agricultural non-point pollution of waters of lakes and streams. Although 70% of South Korea is characterized as mountainous (Bashkin et al., 2002), and there are thousands of small watersheds, there is no detailed N budget at the field or catchment scale for these mountainous regions. Thus, the current study was carried out in the Haean basin, a sub catchment of the Lake Soyang watershed, where the outlet (Mandae stream) is known as a hot spot of agricultural non-point pollution. Exported nitrogen is transported to Lake Soyang, a major drinking water reservoir in South Korea. The Haean basin therefore is an advantageous location not only for calculation of the N budget at landscape scale, but also for a comparison of field level applications with N export calculated for the basin. Two steps for the estimation of N losses from agriculture were used in this study. In a first step, we measured the most important parameters of N budget and simulated additional parameters of secondary importance at the plot and field scale for the five most common crops: (1) cabbage (1a. *Brassica rapa* subsp. *Pekinensis* (Lour.) Hanelt, 1b. *Brassica oleracea* convar. *capitata* var. *alba*), (2) rice (*Oryza sativa*), (3) radish (*Raphanus sativus*), (4) potato (*Solanum tuberosum* L.), and (5) soybean (*Glycine max* (L.) Merr.). Subsequently, the plot scale estimates were extrapolated to field scale and then to the catchment level. In order to validate the results of up-scaling to the catchment level, total N stream water export was identified at the basin outlet.

2. Materials and methods

2.1. Study site and land use

The field experiments were conducted in the Haean-myun basin (128°5′–128°11′E, 38°13′–38°20′N) in Yanggu County, Gangwon Province, South Korea. Elevation ranges between 339 and 1320 m with an average slope of 28% and maximum slope of 84%. The study area falls within the East-Asian monsoon climate 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 usually between June and August and 90% within the growing season from April to October. The agricultural soils of the catchment

Table 1
Selected initial soil characteristics of the top layer (0–30 cm) at the experimental sites. I: the soil characteristics of the dryland field sites and II: the soil characteristics of the rice paddies. BD, bulk density; SOM, soil organic matter; EC, electrical conductivity; CEC, cationic exchange capacity; N_{tot}, total N; C_{org}, organic carbon; N_{min}, mineralized N. Standard error of the mean is given in italics and parentheses.

Sand (%)	Silt (%)	Clay (%)	BD ($g\,cm^{-3}$)	pH	SOM ($g\,kg^{-1}$)	EC ($\mu S\,m^{-1}$)	CEC ($cmol_c\,kg^{-1}$)	N_{tot} ($g\,kg^{-1}$)	C_{tot} ($g\,kg^{-1}$)	N_{min} ($kg\,ha^{-1}$)
I. Dryland field sites										
72.1 (±1.7)	22.4 (±1.2)	5.4 (±0.5)	1.26 (±0.03)	5.8 (±0.11)	10.7 (±1.2)	0.1 (±0.0)	10.3 (±0.5)	0.61 (±0.05)	6.04 (±0.63)	NO_3^-: 93 (±19) NH_4^+: 98 (±11)
II. Rice paddies										
51.4 (±6.5)	38.0 (±4.4)	10.6 (±2.1)	1.14 (±0.02)	6.2 (±0.12)	17.2 (±1.2)	0.05 (±0.0)	12.2 (±0.9)	0.81 (±0.06)	8.72 (±0.70)	NO_3^-: 9.96 (±9.96) NH_4^+: 98 (±6.49)

Table 2
Land use in the Haean catchment in 2009. I: total catchment area and II: croplands.

I. Catchment	ha	%	II. Croplands	ha	%
Crops	1720	27	Soybean	219.9	12.8
Barren	21	0.3	Cabbage	78.8	4.6
Forest	3907	61	Potato	175	10.2
Grassland	427	7	Radish	415.8	24.2
Urban	90	1	Rice	507	29.5
Other	235	4	Ginseng	129	7.5
			Orchards	82	4.8
			Others	112.6	6.5
Total	6400	100	Total	1720	100

can be mainly characterized as terric Cambisols or as Anthrosols (IUSS Working Group WRB, 2007) because of the artificial long-term addition of sandy soil on the top layer of the fields. The four dryland crops rotate annually on the dryland field sites, while rice is cultivated for several years at the same field sites. Therefore, soil data is given for dryland fields and rice paddies separately (Table 1).

About 34% of the bowl-shaped mountainous basin is accounted to agricultural land use (incl. grasslands) (Table 2). Rice paddies cover 30% of the cropped land (excl. grasslands), whereas the four most important dryland crops (radish, soybean, potato, cabbage) account for approx. 52% of the cropped area (Yanggu County Office, 2010). In our study, we did not distinguish between Chinese cabbage and European cabbage, but summarized the two types to cabbage in general. Dryland farming is dependent on natural rainfall and the choice of the cultivated crop is influenced by the timing of the predominant rainfall in relation to the season. While rice is cultivated in the areas of flat land that are flooded annually during the monsoon season (Kim et al., 2007), dryland crops are grown on the slopes in ridge-cultivation systems with PE mulch. The use of mulches, especially plastic mulches, is a common modification of the ridges in vegetable production systems worldwide (Rice et al., 2001). The effects of the PE mulches depend on the material characteristics as well as the color, but include for example weed suppression or improving soil water availability (Lamont, 1993, 2005). Types of plastic mulch include non-degradable, photo-degradable and bio-degradable plastic mulches. The colors of plastic mulches can be black, transparent, white, blue, red, orange, silver, etc. However, black PE mulch is the most widely used mulch in agriculture. On the steep slopes of the catchment, land is a naturally regenerating mixed deciduous forest. The catchment is little affected by livestock farming and not affected by industrial activities.

2.2. *Experimental design, sampling and analysis*

Thirty-one cultivated fields (4–8 replicates for each crop) distributed throughout the catchment were selected for this study. The fields were managed by the respective owners according to local practices and experience, as summarized in Table 3.

Soil samples were taken (five cores from each field) from 0 to 30 cm three times: before fertilizer application, shortly after fertilizer application and at harvest time. The five field replicates were mixed, weighed, and extracted with 1 M KCl solution directly in the field. The extracts were analyzed for NH_4^+ and NO_3^- (UDK 129 Distillation Unit, VELP Scientifica, Italy). Bulk density was determined. The pooled soil samples of the last harvesting were dried at 60 °C and crushed with a mortar to enable sieving (<2 mm) and analyzed for physico-chemical soil parameters (Table 1). Aboveground and belowground crop biomass was measured gravimetrically on all plots at final harvest time (3 plots of 1 m^2 randomly chosen in each field). Immediately after separation of the plant parts, the fresh weights (FW) of leaves, stems, roots, and grains were measured for each plant. Plant parts were oven-dried at 70 °C for at least 48 h for the determination of dry matter (DM). An aliquot of each plant part was finely ground with a ball mill (Brinkman Retsch, MM2 Pulverizer Mixer Mill, Germany) and analyzed for total N and C content (NA 1500, Carlo Erba Instruments, Italy). Atmospheric N deposition was determined as inorganic N inputs (excluding dissolved organic nitrogen (DON)) via bulk precipitation ($n = 2$) including wet deposition and a small amount of undetermined dry deposition. Bulk precipitation was sampled bi-weekly in a 2-year rainfall chemistry monitoring from 2008 to 2010 in an opening near a long-term monitoring site in a forested subcatchment (Jo and Park, 2010). Monthly routine stream water sampling was conducted upstream of the Mugol Bridge at the only catchment outlet, the Mandae stream, from January to December 2009.

Table 3
Local cultivation practice and crop management characteristics of the 5 main crops covering 82% of the agricultural area of the Haean catchment. Plant density gives the distance in cm between two plants in a row. Row density gives the distance in between two rows of crops.

Crop	Growing season	Growth days	Tillage times (+depth in cm)	Fertilization times + (timing)	Fertilizer rates (kg N ha^{-1})	Plastic mulching
Soybean	End May–end October	120–150	1 (15–30)	1 (basal)	Basal: 30 Add.: 0	Yes, black PE
Cabbage	Mid May–end July	75–90	1 (20)	1–2 (basal+ additional)	Basal: 83 Add.: 155	Yes, black PE
Potato	End April–end August	90–120	1–2 (20–30)	1 (basal)	Basal: 137	Yes, black PE
Radish	Beg. June–end August	70–80	1 (15–20)	1–3 (basal+ additional)	Basal: 88 Add.: 164	Yes, black PE
Rice	Mid May–Mid October	160–180	2 (15–30)	1–2 (basal+ additional)	Basal: 50 Add.: 20 + 20	No

Crop	Irrigation	Plant density/row density (cm)	Planting	Seasonal rotation
Soybean	No	25–40/75	Seedling	Only crop of season
Cabbage	No	30–40/60–65	Seedling	Only crop of season
Potato	No	25–30/60–70	Seed	Only crop of season
Radish	No	25–30/60–70	Seed	Only crop of season
Rice	Yes, ground + river water	17–20/15–23	Seedling	Only crop of season

Grab samples of water were collected in midstream approximately 10 cm below the stream surface using PTFE bottles and were kept refrigerated at <4 °C. Within 24 h, the samples were filtered through pre-combusted glass fiber filters (GF/F, 0.7 μm, Whatman, UK) after pre-filtering through a plastic sieve (2 mm). Filtered water samples were then analyzed for NO_3^- and NH_4^+ using an ion chromatograph (DX-320, Dionex, USA). Daily average surface water discharge at the catchment outlet was estimated through a catchment wide spatial water balance analysis. The discharge results were optimized by comparing to and minimizing the difference between temporally variable observed and estimated discharge at the catchment outlet. Load for low-frequency monitoring was calculated using Eq. (1) (Clark et al., 2007).

$$F = K \times Q_r \left(\frac{\sum C_i Q_i}{\sum Q_i} \right) \quad (1)$$

where F is the total solute load carried over a certain time period, K is the conversion factor (here number of seconds in the time period), Q_r is the mean discharge from a continuous record; Q_i is the instantaneous discharge, and C_i is the instantaneous concentration.

2.3. Calculations of N budget and fertilizer N use efficiency

N budgets for the 2009 growing season were defined separately for each field. They are the outcome of an accounting process that consider all N inputs and crop N removal with harvest as N output to a defined soil–crop system over a fixed period of time (total input-approach) (Korsaeth and Eltun, 2008). The positive or negative difference between the respective N input and the N output is called surplus or deficit, respectively. We additionally chose a second approach to respect the complexity and the variety of N loss pathways in a soil–crop system. The selected input-approach (LfL, 2011) puts the N inputs from atmospheric deposition, seed, and non-symbiotic fixation on a level with the N outputs by gaseous emissions and denitrification to respect other N loss pathways than N uptake by crops. Thus, the above-mentioned N inputs were not included in this calculation. Both approaches give the gross N surplus (N input minus crop N) and net N surplus (N input minus harvest N) as a result of the calculations. However, while the TA calculates the maximum N surplus for the respective field sites, the SA includes other N loss pathways by excluding certain N inputs.

For each field site, all major N flows were either measured in the field or estimated using literature, statistical data and simulation modeling. Fertilizer N input data was taken as average values from the years 2007 to 2009 out of statistical yearbooks for Gangwon Province (RDA, 2008, 2009, 2010) because precise indications provided by local farmers were rare. N inputs from biological N fixation (non-symbiotic only) were set using data from Bashkin et al. (2002), while N inputs from symbiotic N fixation were obtained from Herridge et al. (2008). N inputs with irrigation for rice paddies were taken from Dobermann and Cassman (2002). N outputs consisted of crop N removal with harvest (TA) or of crop N removal with harvest, gaseous emissions, and denitrification (SA). The N use efficiency (NUE) was calculated as the amount of harvested N divided by the amount of total N input. The fertilizer N use efficiency (FNUE) was calculated as the amount of harvested N divided by the amount of applied fertilizer N.

The determination of system boundaries in both space and time is a crucial step in the compilation of nutrient budgets (Watson et al., 2002). Within the horizontal dimension of the spatial system boundary, only the managed arable land was included in the field size. Regarding the vertical dimension of the spatial system boundary, soil samples from 0 to 30 cm depth were used as the lower boundary because most of the crop roots were distributed within this depth. Shim and Kim (2005) estimated the discharge of nitrogen from forests in South Korea at 4.67 kg ha^{-1} year^{-1}. We therefore assumed that the forest, although covering 60% of the catchment, did not significantly contribute to the catchment N losses (assumption 1). The budget considered a single growing season as investigated processes did not play an important role during winter time due to cold temperatures and very low precipitation (assumption 2). Furthermore, the agricultural practice of Haean basin includes one crop per growing season and there was no seasonal rotation between crops at the agricultural field sites.

In order to upscale biomass values from plot to field level, we used information on row and plant density for each crop type to calculate the number of plants within 1 ha. To up-scale the N budgets from the field to the catchment level, statistical data on agricultural land use for the Haean catchment in 2009 was used (Yanggu County Office, 2010). The contribution of the five observed crop types to the catchment N surplus was then estimated by using the net N surplus in soil (kg ha^{-1}) of the respective crop type and its areal dimensions (ha) in the basin. The contribution of the other land use systems of the Haean catchment, which were not measured in this study, was calculated by using estimated net N surpluses in soil (kg ha^{-1}) of the respective land use system and its areal dimensions (ha) in the basin.

Net N surpluses from urban areas and forests in South Korea were taken from Shim and Kim (2005) and estimated at 52 kg ha^{-1} and at 4.67 kg ha^{-1}, respectively. Ginseng (*Panax ginseng* C.A. Mey.), bonnet bellflowers (*Codonopsis* Wall.), and orchards (*Mallus* Mill., *Pyrus* L., *Prunus persica* (L.) Batsch, *Vitis vinifera* L.) were estimated at 39.4 kg ha^{-1} for the growing season based on the findings of Bruin et al. (2010). Other crops with low areal contribution were pooled in one group and the mean value of the five measured crop types was set as their net N surplus. The net N surplus of the grasslands (dominantly ryegrass) was estimated at 56 kg ha^{-1}, which is 1/5 of the mean value of the net N surpluses of the five measured crop types because N leaching from grasslands is generally thought to be small (Dowdell and Webster, 1980).

2.4. Statistical analysis

Statistical analysis was carried out using the statistical software package STATISTICA (version 10, StatSoft Inc., Tulsa, USA), with a significance level of $P \leq 0.05$. All variables were tested for normal distribution (Shapiro–Wilk-test) and homogeneity of variance (Levene-test). Differences in central locations (mean) between the groups (crop types) were analyzed using the one-way ANOVA. In order to decide, which groups (crop types) were significantly different from each other, a post hoc test (Least Square Difference) was applied.

3. Results

3.1. Biomass production, N crop uptake and N crop output at field scale

Production of mean dry biomass (DM) differed significantly between the five crops (Fig. 1). While dry biomass was highest for rice and potato (>14 Mg ha^{-1}), the mean DM produced by both radish and cabbage was the smallest at less than 10 Mg ha^{-1}.

Due to low crop N contents (Table 4), rice and potato showed rather low amounts of total N taken up by plants at harvest time (Fig. 2). However, among rice, potato, radish and cabbage, crop type did not play a role in the N uptake at final harvest ($P > 0.05$). Large dry biomass combined with high crop N content did lead to a significantly higher N uptake by soybeans (322 kg N ha^{-1}) (Table 5). The differences between crops in residue N remaining after harvest were fairly high. For rice and soybean, more than 50% of the

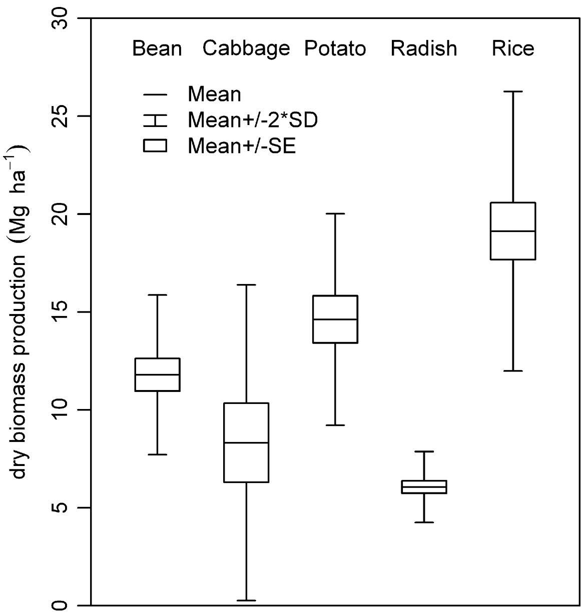

Fig. 1. Measured biomass (dry) of the five key crops in 2009.

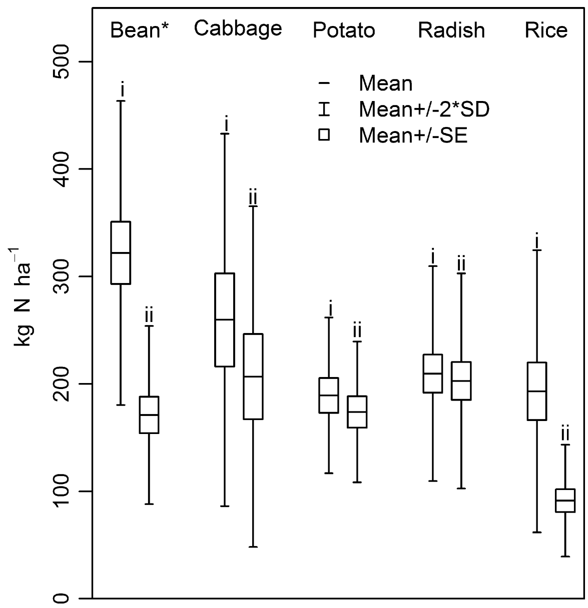

Fig. 2. Crop N uptake (i) at harvest and crop N removal (ii) with harvest of the five crops in 2009. *Significant difference between i and ii. Crop N uptake at harvest illustrates the crop N of all crops at the field site. Crop N removal illustrates only the crop N, which is removed from the field site with harvest. Results are shown in Table 4.

crop remained at the field site, whereas only small amounts of root material and dead plant material were left in potato and radish fields after harvest. This led to a lower N removal than total N uptake for all crop types, although only soybeans displayed a significantly lower N removal with harvest than total crop N uptake.

Table 4
Measured crop N content in % of the five main crops in the Haean catchment. Values are shown with the standard error of the mean (SE) in italics.

Crop type	Total crop N (%)	SE
Bean	2.7	0.1
Cabbage	3.3	0.2
Potato	1.4	0.1
Radish	3.4	0.2
Rice	1.0	0.1

3.2. Components of N budget and N use efficiency

The main N input source (210–318 kg N ha^{-1}) of rice, radish, potato and cabbage with an average of 55% of total N input was related to the application of mineral fertilizers. Differences in N fertilization rates for cabbage are shown in Table 4, in which the range of N fertilization for cabbage is given. In general, European cabbage

Table 5
N budgets with details of N input and N output for the 5 main crops in the Haean catchment. Values are shown with SE and range (mean n = 4–8). All components of N budget are given in kg N ha^{-1}. The range of the fertilizer N application found for cabbage can be explained with the pooling of European and Chinese cabbage, which show different fertilizer N application rates.

	Soybean $\bar{x}$/SE/range	Cabbage $\bar{x}$/SE/range	Potato $\bar{x}$/SE/range	Radish $\bar{x}$/SE/range	Rice $\bar{x}$/SE/range
N input					
Natural					
Soil N_{min} NO_3^-	93/79/18–260	93/79/18–260	93/79/18–260	93/79/18–260	10/10/0–40
Soil N_{min} NH_4^+	98/47/39–186	98/47/39–186	98/47/39–186	98/47/39–186	59/6/47–74
Deposition N	15	15	15	15	15
Fixation N	180	15	15	15	45
Sum	386	221	221	221	129
Management					
Fertilizer N	33	296/–/318–274	210	254	234
Irrigation N	0	0	0	0	15
Seed N	3	3	1.5	1.5	3
Sum	36	299	211.5	255.5	252
Total					
N input TA[a]	422	520	433	477	381
N input SA[b]	404	487	401	445	318
N output					
Crop N	322/29/199–39	260/43/185–368	189/16/145–233	209/18/119–273	193/27/137–283
Residue N	151/16/99–190	53/11/36–84	15/2/9–43	7/2/0–19	102/17/67–162
Sum					
Harvest N[c]	171/17/100–205	207/40/143–319	174/15/132–211	203/18/115–267	91/11/65–136

[a] The results were calculated with the total-input approach (N input = fertilizer N, soil N_{min}, deposition N, fixation N, Irrigation N, seed N).
[b] The results were calculated with the selected-input approach (N input = fertilizer N, soil N_{min}, irrigation N, symbiotic N fixation).
[c] Crop N removed with harvest.

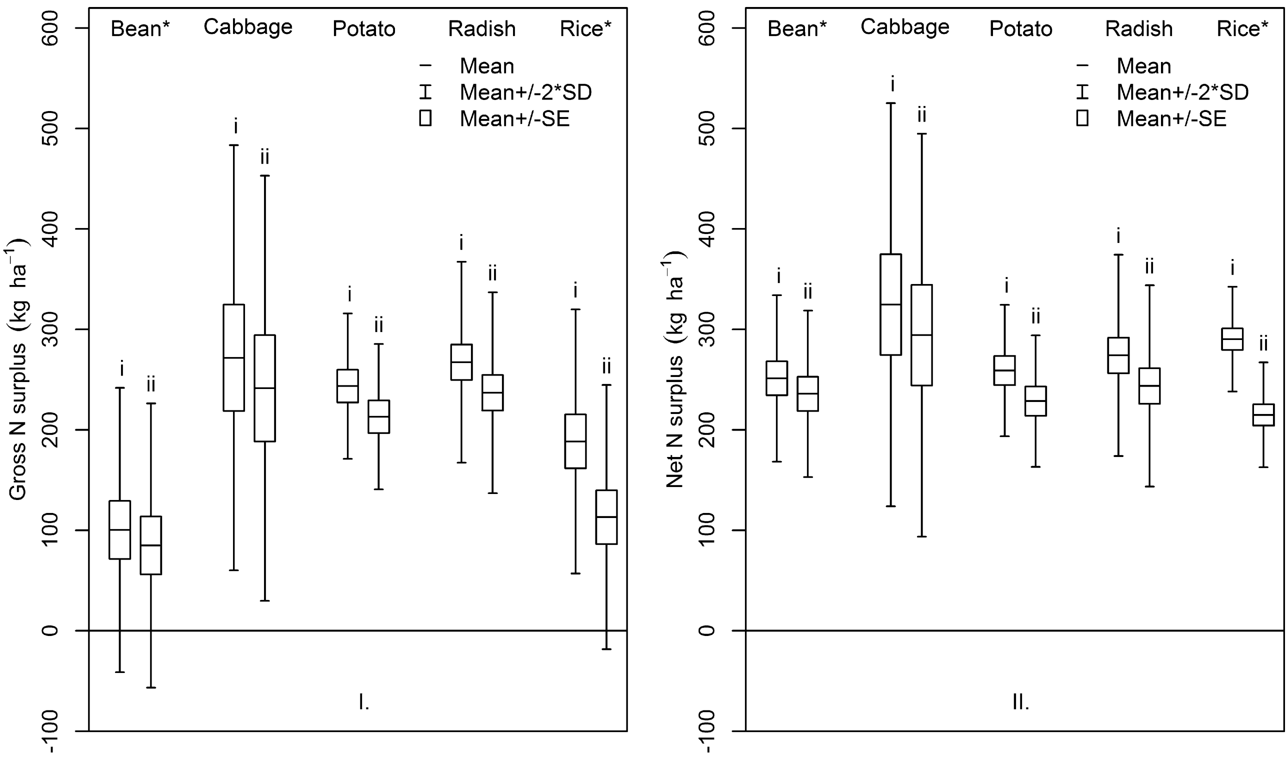

Fig. 3. (I) Gross N surplus (N input minus total crop N) and (II) net N surplus (N input minus harvest N) calculated with two different approaches. Potential deficits at soybean fields result from the high N uptake by plants and a low fertilizer N input. i: total input-approach; ii: selected input-approach. *Significant difference between I and II.

is characterized by a lower fertilizer N application (274 kg N ha^{-1}) than Chinese cabbage (318 kg N ha^{-1}). In the further text, no distinction will be made between Chinese and European cabbage due to an inadequate amount of replicates. The mineral N fertilizer input for soybean was 33 kg N ha^{-1}, which represents 8% of the total N input. The main N input source for soybean (~43%) was biologically fixed N (symbiotic). Soil N_{min} at the beginning of the growing season averaged to 41% of the N input for soybean, cabbage, potato and radish. For rice, however, it only accounted for 18%. Other N input sources played only a minor role. Finally, N outputs with harvest were on average 38% of the N inputs.

The calculation of N budgets with the TA (i in Fig. 3) revealed that each crop type showed gross and net N surplus at the end of the growing season because all crop types but soybeans had high fertilizer N rates. Soybean, however, had high biological N fixation, which also led to high total N inputs. Cabbage, radish, potato and rice showed a mean gross N surplus in the range of 190–270 kg N ha^{-1} $year^{-1}$ due to the high N fertilization rates (Fig. 3). As a result of its high crop N uptake and low mineral N fertilizer input, soybean showed a lower gross and net N surplus compared to the other crops ($P < 0.05$). Differences between gross and net N surplus were significant for rice and soybean because of the large portion of plant residues, which remained at the field after harvest. Since N loss pathways were considered in the SA (ii in Fig. 3), the results generally showed lower gross and net N surpluses for all crops. Gross N surplus ranged from 85 to 250 kg ha^{-1} with a lower gross N surplus for rice and soybean ($P < 0.05$). Differences between gross and net N surplus were again significant only for rice and soybean.

Mean net N surplus of the five crops in the catchment amounted to 280 kg N ha^{-1} (TA) and 243 kg N ha^{-1} (SA), resulting from a mean N input of 447 kg N ha^{-1} and 415 kg N ha^{-1} and a mean crop N removal with harvest of 169 kg N ha^{-1}. The results calculated with the two approaches showed very similar findings. This indicated the dominant role of mineral fertilizer N and mineralized inorganic N available in soil (N_{min}) as N input source in these agroecosystems. The crop NUE for the TA increased in the order: 24% (rice) < 39.5% (cabbage) < 40% (potato) < 40.5% (bean) < 43% (radish) and showed an average of 37%. The crop NUE for the SA increased in the order: 30% (rice) < 42% (cabbage/bean) < 43% (potato) < 45.5% (bean) < 43% (radish) and showed an average of 40.5% (Fig. 4). For the latter approach no crop type showed any effect on NUE ($P > 0.05$), whereas the first approach found a significantly lower NUE of rice.

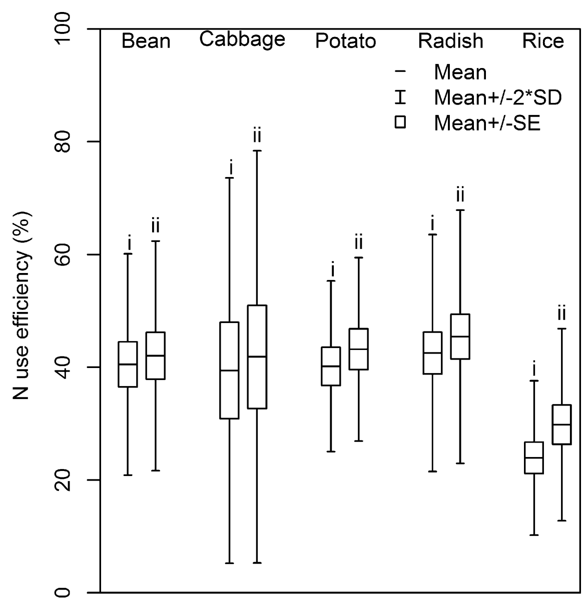

Fig. 4. N uptake efficiencies of the five key crops. i: calculated with results of the total input-approach; ii: calculated with results of the selected input-approach.

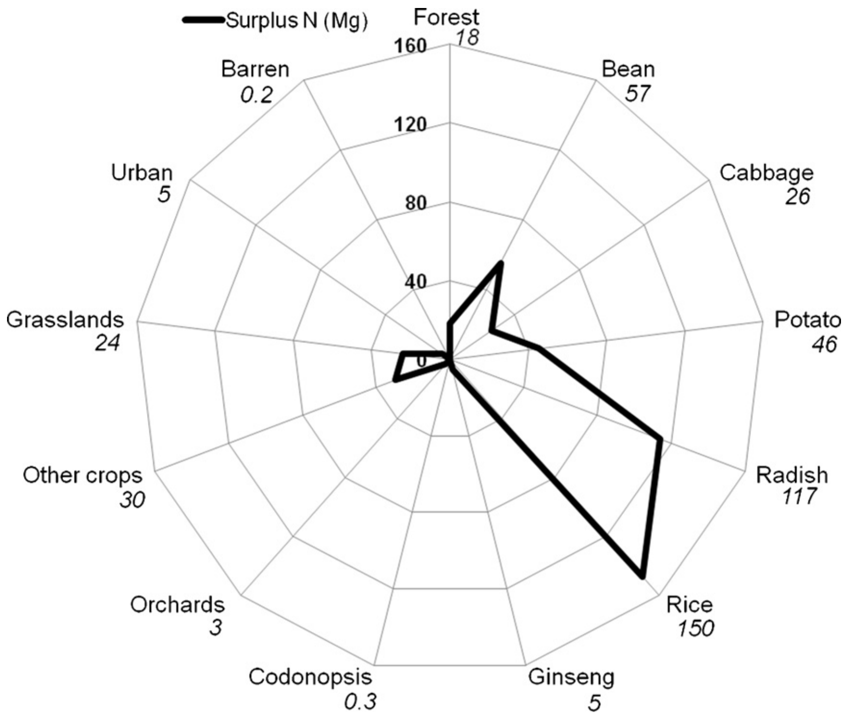

Fig. 5. Maximum net N surplus (Mg) for agricultural land and other land use categories at the catchment scale in 2009. Net N surplus was calculated with the total input-approach. Values in *italics* give the amount of total net N surplus of each land use category.

The mean fertilizer N use efficiency increased in the order: rice (39%), cabbage (69%), radish (80%), and potato (83%), resulting in a mean fertilizer N use efficiency of 68%. Rice was the only crop with a significant effect on fertilizer NUE. Fertilizer N use efficiency for soybean was not calculated as mineral N fertilizer was not an important N source and only accounted for 8% of N input.

3.3. N surplus at the catchment scale

Total N surplus in the catchment amounted to 473 Mg when calculated with net N surplus derived from the TA and to 403 Mg when calculated with net N surplus derived from the SA (Fig. 5).

Both approaches showed that agricultural activities accounted for over 90% of the N surplus at the catchment level even though their areal contribution was only 34% (incl. grasslands). The forest contribution to the N surplus was estimated at 4.7 kg N ha^{-1} $year^{-1}$ (Shim and Kim, 2005), which averaged to 18 Mg $year^{-1}$ for the forest part of the entire catchment (3907 ha) and was therefore negligible. Activities such as housing and industry (urban) did also not play a relevant role in the N budget at catchment scale. The catchment is on the one hand only little affected by industrial activities or housing (90 ha) and secondly, the N contribution of these activities was estimated to be comparatively low (52 kg N ha^{-1}).

For both N budget approaches the contribution to N surplus at catchment scale within the agricultural land use increased in the order cabbage (26 Mg) < potato (45 Mg) < soybean (55 Mg) < radish (114 Mg) < rice (147 Mg), while ginseng (5 Mg), codonopsis (0.3 Mg), orchards (3 Mg) and other crops (30 Mg) did not play a significant role in 2009. Perennial crops like ginseng, codonopsis, fruit orchards and vineyards were assumed to have a lower N surplus due to lower fertilizer N inputs (Ledgard et al., 1999). One reason for this assumption is that the fertilizer N recommendations of the RDA were much lower than for the other five crops. The recommendation for codonopsis was 60 kg N ha^{-1}, for orchards it ranged between 20 and 70 kg N ha^{-1} depending on fruit type and year of growth, and ginseng was usually cultivated without the application of any chemical fertilizer (RDA, 2006). We assumed in this study that the farmer followed this application rate, although the actual fertilizer application for the five key crops of the catchment showed that the farmer often exceeded the recommended application rates. Secondly, Ramos et al. (2002) observed that N leaching varied from 240 to 340 kg N ha^{-1} $year^{-1}$ in fields cultivated with onions as well as potatoes and therefore represented 66–70% and 38–65% of the total N input into the onion and potato fields, respectively. N leaching losses in orchards, however, were in general lower than 100 kg N ha^{-1} $year^{-1}$ and represented therefore only around 33% of the total N input. Within the group of the measured key crops, rice and radish contributed twice as much as the other crops to the total N surplus. The high contribution of rice and radish at the catchment scale resulted from the high net N surpluses at the field scale (290 kg N ha^{-1} and 274 kg N ha^{-1}, respectively) as well as from the large area they covered within the catchment (507 ha and 416 ha, respectively). The very high N surplus of cabbage (325 kg N ha^{-1}) at the field scale was constrained by the small area it covered (79 ha) and hence resulted in a low contribution at the catchment scale.

3.4. N export in the catchment outlet

Stream water N in the catchment outlet amounted to a total of 321 Mg NO_3^- and 8 Mg NH_4^+, resulting in 329 Mg inorganic N for the 180 days of observation from April 15 to October 31, 2010. During this period, mean discharge was 8322 l s^{-1}. The highest discharges were observed during the summer monsoon season with discharges higher than 100,000 l s^{-1} at July 15 and August 13, whereas the lowest discharges were found at the beginning and at the end of the growing period, when total precipitation was low, with discharges lower than 2500 l s^{-1} at April 24 and October 9 (Fig. 6). Consistently, the nitrate and ammonium export with the stream water was also highest during the summer monsoon season with an export higher than 250 g s^{-1} and 4.5 g s^{-1}, respectively, at July 15 and August 13. Lowest export of nitrate and ammonium

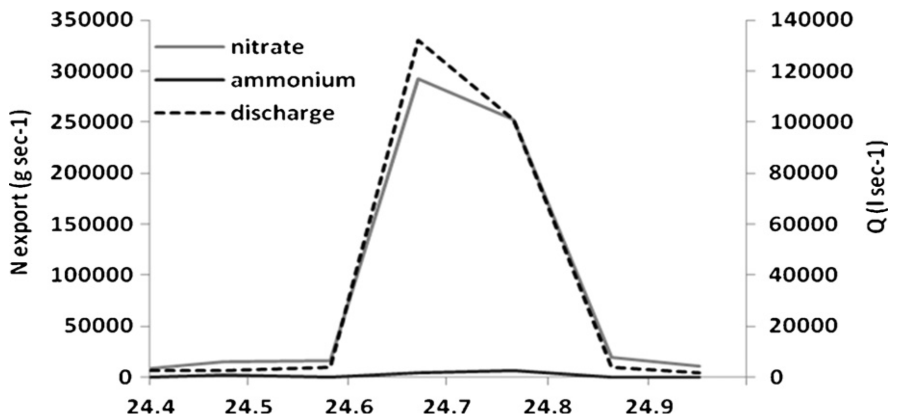

Fig. 6. Stream water data of the Mandae stream. Shown are the discharge Q (l s^{-1}) and the nitrate as well as the ammonium export (g s^{-1}) with the only outlet of the Haean catchment during the growing season 2009.

with the stream water was observed at the beginning and at the end of the growing period with an export lower than 11 g s^{-1} and 0.6 g s^{-1}, respectively at April 24 and October 9. Stream water concentration for nitrate and ammonium, however, averaged to 4.2 mg l^{-1} and 0.2 mg l^{-1}, respectively.

4. Discussion

4.1. N use efficiency and fertilizer N use efficiency

The results of the mean NUE of the five key crops of the catchment support earlier findings, which found the NUE of crops grown in South Korea to be the lowest in Asia at 38% (Bashkin et al., 2002). The low NUE of rice is responsible for the very low mean NUE of all crops. The data for the individual crops from our study showed also high consistency with findings from other studies that observed a NUE of rice in the range of 20–40% in field studies (Cassmann et al., 1993) and a NUE in the range of 40–60% for upland crops, such as potato, soybean, and maize (Vlek and Byrnes, 1986). The measured data from this study, however, was found to be at the lower end of the usual range, which was observed by the mentioned studies. While rice showed the lowest NUE in both approaches compared to the other four crops and was found to be significantly lower in one of the two approaches, the group of dryland crops did not show any significant difference in NUE. High N losses in the summer monsoon season were responsible for the comparatively low efficiencies of all dryland crops. Simulation of N leaching losses in a radish cultivation in the Haean catchment showed that most of the supplied fertilizer N (>50%) percolated deeper than the root zone during the growing season and was therefore lost to groundwater (J. Kettering, personal communication). At sloping field sites, the N loss with surface runoff could additionally play an important role (Gardi, 2001). Soil erosion measurements in the Haean basin in 2010 showed that more than 1 kg N ha^{-1} was transported on steep dryland fields by surface runoff during single storm events (>70 mm) (S. Arnhold, personal communication). However, at the field sites used for this study surface runoff and N export with surface runoff was not experimentally measured.

On average, 65% of the mineral N fertilizer was applied prior to planting, which made it vulnerable to N losses, especially early in the season. Additionally, the applied fertilizer N rates in the Haean basin exceeded the recommendations given by the RDA for all crops except radish and soybean. The added fertilizer N rates exceeded the recommendations by 2.3, 1.5 and 1.2 times for rice, potato and cabbage, respectively.

In this study, we found very high fertilizer N use efficiencies for the key crops in the Haean catchment. Much lower fertilizer N use efficiencies, namely ∼27% for summer radish, were obtained from a ^{15}N field experiment for the Haean basin in 2010 (J. Kettering, personal communication). The contrast between the results obtained with and without ^{15}N exposes the strong impact of other N sinks and sources on the calculation method used in the present study. Therefore, the calculation method used for this study largely overestimated fertilizer N use efficiency.

4.2. N budget at field scale

The total N outputs with crop removal were only about 38% and 40% of the N inputs for the TA and the SA, respectively. Firstly, this gives an indication for the high consistency between both approaches, despite their different calculation methods. This high consistency illustrates the dominant role of mineral fertilizer N and mineralized inorganic N available in soil as N input source for four of the five observed crops of the catchment. The difference between TA and SA was also small for soybean, although fertilizer N input only played a minor role. This was due to the soybeans' ability to biologically fix N, which was together with soil N_{min} the dominant N input source in soybean cultivations. Secondly, it also implies considerable N losses from the plant–soil system and consequently an export to either the atmosphere or to the bodies of water. The homogeneity of the soil texture of the upper soil layers resulting from the addition of sandy soil to the fields for decades most certainly led to an increased risk of quick N percolation with the soil water to deeper layers instead of N retention in the soil. The accumulation of N in the upper sandy layers of the soils with their poor sorption characteristics was therefore assumed to be insignificant during the summer monsoon season. The low N outputs with harvest and the high N inputs resulted in positive gross N and net N surpluses for both approaches. The differences in gross N and net N surplus were significant for rice and soybean, indicating the need to adopt ways and means to manage the plant residues to reduce N surplus and subsequently N losses.

However, for gross and net N surplus as well as NUE a wide variance was observed in the results. The variance in the results was highest for soybean and cabbage. In the case of cabbage, it implies a difference between agricultural management of European and Chinese cabbage and consequently a difference in N surplus and NUE between European and Chinese cabbage, which were summarized for the analysis to allow an ANOVA. The comparison of the N field budgets for the Haean basin with the general N budget for agricultural land in South Korea (Bashkin et al., 2002) showed somewhat lower N surpluses calculated by the latter. In their study, an average N surplus of 215 kg N ha^{-1} was calculated, resulting from a N input of 347 kg N ha^{-1} and a crop N output of 132 kg N ha^{-1}. The

N input in both studies differed in its dimension as well as in its composition. The most important difference in these two studies and the most important factor for the different results is the N input with soil N_{min} and manure. While manure, which is used as organic fertilizer in agriculture, is added purposely at the beginning of the growing season to contribute to the fertility of the soil, the soil N_{min} measured at the beginning of the growing season results from the plant residues remaining at the field sites after harvest. Our results further conform to findings from intensive agricultural systems in the Taihu region in China, where agricultural management is similar to that in South Korea and annual N surpluses were in the range of 217–335 kg ha^{-1} year^{-1} (Richter and Roelcke, 2000).

4.2.1. Plant residue management

Soybean showed a significantly higher crop N uptake than the other key crops in the catchment. Additionally, soybean showed a significantly lower crop N removal with harvest compared to its crop N uptake. This difference offers a possibility for potential N savings especially considering that the N remaining in the soil is in organic form and consequently will remain in the soil until mineralization to nitrate. This applies also to rice, even if the crop N removal with harvest was not significantly lower than the N uptake. Studies in Japan also showed that the N accumulation resulting from nitrification in the fallow season could be a key source of N leaching in rice fields when fields become re-flooded before rice transplanting in the following year. They even conclude that particular attention should be paid to this phenomenon (Luo et al., 2011). For both rice and soybean, more than 50% of the total biomass remained at the field site or was partly returned in the Haean basin. On average, this added around 150 kg N ha^{-1} and 100 kg N ha^{-1}, respectively, to the N surplus at the field scale. The amount was probably even higher since the calculation assumed that each plant was harvested and removed from the field site. In contrast to our careful harvesting of 1-m^2-plots, some plants were not harvested and remained at the field site due to shortcomings in size, shape or condition. According to our rough visual estimations, management residues at the field site accounted for about 10% of the total plant amount at the field site. The actual amount of plant residues at the field site was highly dependent on the individual farmer, the further use of the plant residues by the farmer, the market price and selling conditions, and other factors. This complicates the generalization of the amount of plant residues and the determination of a sustainable management strategy.

However, a more sustainable management of rice and soybean plant residues could play a relevant role in reducing N surpluses. Rice husks could be used for the production of bio-char, which then could be applied to any cropping system (Lehmann et al., 2006; Lehmann and Rondon, 2006). The incorporation of the rice crop residues after its harvest leads to the buildup of SOM, soil N, P, and K, and the crop residues add a substantial amount of organic carbon (C). This again leads to a slowdown of the decomposition and the immobilization of inorganic N due to a wide C/N ratio of the crop residues compared to bean and thus to a reduction of the N leaching (Choudhury and Kennedy, 2005; Mandal et al., 2004). The conversion of biomass C to bio-char C, however, leads to the sequestration of about 50% of the initial C compared to the low amounts retained after biological decomposition (<10–20% after 5–10 years) and therefore yields more stable soil C than direct land application of biomass (Lehmann et al., 2006). Bio-char can therefore be used to sequester C and to improve the production potential of crops.

4.2.2. Fertilizer N and soil N_{min} management

For potato, radish, and cabbage, however, the residue management did not play a relevant role in balancing N budgets because only negligible amounts of plant residues remained at the field sites after harvest. For each of these three crops, N input with mineral fertilizer was found to be the main contributor to the total N input at the field sites. N input with mineral fertilizer was also the biggest single N source for rice. Fertilizer N input did play a negligible role only at the soybean fields due to the soybeans' ability to biologically fix N. The local farmers exceeded the fertilizer N recommendations given by the RDA by 1.5- and 1.2 times at potato and cabbage fields, respectively. Korean rice farmers applied even more chemical fertilizer than the global average (Korean Ministry of Agriculture and Forestry, 2002) and exceeded the recommendation by 2.3 times. An investigation using ^{15}N fertilizer regarding the recommendations provided by the RDA found that a reduction of 40–60% of the fertilizer N was adequate to achieve maximum radish yields in the Haean catchment (J. Kettering, personal communication). This implies that the fertilizer N rates applied by the local farmers in Haean catchment could be drastically reduced. Additionally, 65% of the mineral N fertilizer was applied prior to planting at a time when plant growth and crop N uptake is small. This excessive supply of N at the early cultivation stage and during the summer monsoon season is most certainly prone to leaching and to surface runoff. Therefore, splitting the fertilizer N applications into several applications would help to avoid high N losses at the beginning of the growing season and during heavy rain events. Consequently, there is a substantial scope to reduce fertilizer N inputs and subsequently reduce N surpluses.

The second biggest contributor to the total N input for potato, radish and cabbage was soil N_{min}. On average, 190 kg N_{min} ha^{-1} was available for plant uptake at the beginning of the growing season before fertilization. Our measurements showed very high initial soil nitrogen stocks in spring with the mean nitrate soil stock being slightly higher than ammonium, which was surprising since the capacity for fixing NH_4^+ is much higher than for NO_3^-. The results were higher than findings from a study conducted in the North China Plain, which also showed that N mineralization (91–153 kg N ha^{-1} year^{-1}) was a significant input, particularly in the wet summer season (Liu et al., 2003). As the climate in China is generally dryer, net N mineralization rates in South Korea are probably higher. However, soil mineral N was definitely the second biggest N source for all of the investigated agro-ecosystem of the Haean catchment, but the findings seem to be somewhat overestimated. Mineral fertilizer N and soil N_{min} contributed together over 90% to the total N input for potato, radish, and cabbage, while at rice and soybean fields their contribution amounted to 80% and 53%. The synchronization of these two important N input sources and the integration of fertilizer N and soil N_{min} supply are required to (1) reduce the mineral fertilizer N input and (2) to reduce the N surpluses. The N_{min} content in the soil at the planting time in the fields of the four dryland crops was greater than 190 kg ha^{-1}. The fertilizer application could therefore be greatly reduced if some recommendation system similar to the N_{min} system used in European countries was adopted (Ramos et al., 2002). Additional measures, which were effective in large parts of the world, are among others the use of cover crops during fallow, the use of slow-release fertilizer, and the use of nitrification inhibitors (Di and Cameron, 2002).

4.3. N Budget and N export at the catchment scale

Agricultural land use was found to be the main contributor (>90%) to N surplus at the catchment scale. Agricultural N surplus for the two approaches added up to 449 Mg and 380 Mg. However, N surplus for forest and urban sites were only estimated with the help of other studies and some uncertainties are therefore related to these numbers. Industrial and housing activities, however, covered only small parts of the catchment or were not existent at all and their importance for the total N surplus at the catchment scale was therefore rather low. Forest, on the other hand, covered the largest part of the basin. The contribution from forests was estimated to be about 5 kg N ha^{-1} $year^{-1}$ (Shim and Kim, 2005). This estimation showed a high consistency with the findings that no significant N leaching to only intermediate levels of N leaching occurred from forests at an atmospheric N deposition of up to 25 kg N ha^{-1} $year^{-1}$ (Dise and Wright, 1995). Atmospheric N deposition in Haean catchment was measured to be around 15 kg N ha^{-1} $year^{-1}$ and therefore insignificant to intermediate levels of N leaching are by all means reasonable for the Haean basin.

The estimation of which crop type was the biggest contributor to the N surplus is of high importance for studying N pollution by non-point sources. Observing each crop separately, rice covered the largest area and was therefore the largest single contributor, followed by radish and soybean. N leaching losses in rice paddies, however, depend strongly on the fertilizer N treatment during the rice growing season. Composted rice straw plus soybean cake produced leaching losses, which were 65–75% lower than those with the application of chemical fertilizer (Luo et al., 2011). N leaching is usually lower in rice than in dryland crops, because of the presence of the low-permeability layer. However, this layer was only little pronounced in the rice paddies in Haean basin. Studies in China additionally showed that N loss through surface runoff can be even more important than N leaching losses in rice paddies (Tian et al., 2007; Zhao et al., 2012). However, N accumulation resulting from nitrification in the fallow season could be a key source of N leaching when fields become re-flooded before rice transplanting in the following year (Luo et al., 2011). Perennial crops like ginseng, *Codonopsis*, fruit orchards and vineyards have a fairly lower N surplus due to their low fertilizer N requirement (Ledgard et al., 1999) and additionally they covered only small parts of the catchment in 2009. Their contribution to the N surplus at the catchment scale was therefore low. We assumed in this study that the farmer followed the application rate recommended by the RDA, although the actual application rates of the five key crops of the catchment showed that the farmer often exceeded the recommended application rates.

The N surpluses are indicators of the potential N loss from the soil–plant system, but they do not indicate or distinguish between different N loss pathways. To determine the N loss from leaching and from surface runoff, which in particular occur with heavy rain storm events, we compared the agricultural N surplus with the stream water N export in the only catchment outlet. The seasonal export of inorganic N in the Mandae stream was estimated to be 329 Mg and therefore represented 73% of the agricultural N surplus calculated with the TA and 86% of the agricultural N surplus calculated with the SA. This means that up to 86% of the N surplus was transported to bodies of water by subsurface and surface flow and exported from the catchment by stream flow. Leaching most certainly played a relevant role in the flat agricultural fields with dominantly sandy soils. A N leaching study in Haean catchment using ^{15}N showed that up to 70% of the applied fertilizer N was lost in a flat agricultural field site and that the majority of the losses was contributed to N leaching (J. Kettering, personal communication). However, at the sloping fields of the catchment, it was shown that N loss with surface runoff might be an important factor. While the SA approach included N loss pathways like crop N uptake, gaseous emissions and denitrification, the TA approach did not consider any other N loss pathway but crop N uptake in its calculation. The SA hence implied that 13% of the agricultural N surplus was lost by gaseous emissions or denitrification.

4.3.1. Land use change

For practical recommendations, it should be considered that land use in the Haean catchment has changed between 2002 and 2009. While the cultivation area of cabbage decreased by 44%, the cultivation area of radish, soybean, and potato increased by 46%, 25%, and 52%, respectively (Yanggu County Office, 2003, 2010). The contribution of cabbage, which showed the highest single N surpluses for all calculations, is going to be further reduced due to its decline in area. The current most evident land use change, however, concerns ginseng and orchards. While the cultivation area of orchards has increased in the same time span by 745%, ginseng cultivation started in 2005 in the Haean catchment and increased since then by approximately 30 times.

The increase of viniculture and pomiculture was mainly enhanced by the regional warming observed in South Korea due to climate change, which widely enlarged the options of fruit-growing (Chung et al., 2004). In fact, the area, which was covered by ginseng and orchards, was still small in 2009 but will probably play a larger role in the upcoming years. With the lower mineral N fertilizer requirement of the perennial crops, their increased cultivation and the subsequent decreased cultivation of the five current key crops could actively help reduce the total N surplus at the catchment scale. Additionally, N losses induced by tillage as well as N losses by surface runoff, which increasingly occur in annual cultivations, could be reduced at the same time. This observed trend of land use change from annual to perennial crops assists the reduction of N surplus at the field and the catchment scale but shows, however, only a spatially limited applicability for the future. One has to consider that cabbage and radish are important parts of the Korean diet and a decrease in their production in favor of orchards and ginseng could lead to increasing pressure for high local yields, and to delocalization of the same cultivation problems to other agricultural areas. The replacement of rice, a staple food of Asia, by ginseng or fruit trees is therefore an effective and promising but spatially limited option for developing more sustainable practices. The most effective action to reduce N surplus at catchment scale is to reduce the fertilizer N application rates at the field scale.

5. Conclusions

The large agricultural N surplus showed a considerable lack of sustainability of local agricultural practices. The gross and net N budgets for all five crop types were found to be positive. Based on the small differences between the results of the two approaches we identified fertilizer N as well as soil N_{min} as the dominant N input sources. As fertilizer N application was the major N input (>50%) for all crop types except soybean, the reduction of the fertilizer N was identified as the major scope of action for N savings at the field scale. A closely linked and urgently required action is the synchronization of the fertilizer N and the soil N_{min}, which contributed together between 50 and 94% to the total N input. The large amount of fertilizer that is applied prior to planting (>60%) at the beginning of the growing and the monsoon season indicated that matching the timing and the application rate to the plants' N need could help reduce the fertilizer N rates and increase the low NUE of all five crop types. For rice and soybean cultivations, the total or partial return of plant residues after harvest additionally contributed a significant amount to the agricultural N surplus. A more sustainable plant residues management, for example the use of rice husks to produce bio-char, is a further possibility to reduce the N surpluses. Finally, potato, radish, and cabbage are harvested in the mid-growing season and during the monsoon season, when the fallow fields are especially prone to leaching and surface runoff. The use of short-term rotational crops would therefore be beneficial to reduce the potential of N leaching after harvest.

Based on the calculated catchment N surplus of >400 Mg, it was revealed that the five main crops accounted for over 80% of the total catchment N surplus, even though their contribution to the area was only around 20%. A land use shift from these five annual crops to perennial crops with lower N inputs was therefore found to be a promising chance to reduce N surpluses at the catchment scale. However, as the perennial crops cannot replace the importance of the five key crops for the Korean diet this shifting has only a spatially limited practical relevance. The comparison of the catchment N surplus with the stream N export revealed that 73–86% of the agricultural N surpluses were transported to water bodies in the catchment. N losses with leaching and surface runoff were therefore identified as the main N loss pathways in the catchment.

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