Budget and fluxes of nitrogen in mountainous agroecosystems in a summer monsoonal climate under intensive land use

Dissertation

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Summary

A balanced nitrogen (N) cycle in intensively managed ecosystems is necessary as it underpins other ecosystem services. This study evaluated the agricultural practices in a typical mountainous catchment in South Korea in respect to N dynamics and their potential effect on water quality with the aim to develop options for a more sustainable catchment management.

In the first study, we used two approaches to calculate N budgets for the 5 key crops of the basin at the field scale. The gross and net N budgets for all 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 source (>50%), its reduction is the major scope of action for N savings at the field scale. A closely linked action is the synchronization of fertilizer N with soil N_{min}. The large amount of fertilizer that is applied prior to planting (>60%) at the beginning of the monsoon season revealed that split applications could help reducing the fertilizer N additions and increase the low N use efficiencies (NUE). Based on the significant differences between gross and net N surplus for rice and bean fields, we identified the high amount of plant residues remaining after harvesting (>100 kg N ha^{-1}) as a further factor for potential N savings. The 5 main crops accounted for over 80% of the total catchment N surplus (>400 Mg), even though their contribution to the area was only around 20%. A land use shift to perennial crops with lower N inputs was therefore found to be a possible but spatially limited chance to reduce N surpluses at the catchment scale. The comparison of catchment N surplus with stream N export revealed that 73-86% of the agricultural N surpluses were transported to water bodies in the catchment by either leaching or surface runoff.

In the second study, we followed the fate of fertilizer N in a ridge and furrow (R/F) cultivation with polyethylene (PE) mulch by using ^{15}N tracer. N leaching was simulated with Hydrus 2D. The comparison of 4 N fertilization levels (0, 150, 250 and 350 kg NO_3-N ha^{-1}) revealed that already 150 kg NO_3-N ha^{-1} is sufficient to reach the maximal yield of radishes. Based on the low results of fertilizer N use efficiency (FNUE), we recommend two applications during the first 25 days of growth and a further application around day 50. These split applications adjusted to the plants' needs increase the FNUE of the radish and decrease the fertilizer N losses during the growing season. However, split applications might be impractical in plastic covered R/F cultivations because mechanical equipment to apply fertilizer under the PE mulch is required. Based on the finding that ^{15}N retention in soil and nitrate 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 nitrate concentration in seepage water and did therefore not effectively protect the fertilizer in the ridges from percolation. Based on the simulation results, we found that the ridges and furrows contributed approximately an equal amount of leached N to the total amount. We therefore conclude that the PE mulch provided little protection for the fertilizer N in the ridges during heavy rainfall. N leaching amounts were further found to increase linearly with an increase in N addition rate as it is well known for R/F cultivations without PE mulch. The PE mulch did therefore not prevent the linear increase in leaching with an increase in fertilizer N addition. We summarize that without the use of additional measures such as split applications of fertilizer, the application of PE mulch in a summer monsoon climate with heavy rainfall events does not positively influence the N leaching rates.

In the third study, we monitored soil water dynamics in the field and used this data set to simulate the influence of PE mulch on water fluxes with Hydrus 2D. We simulated soil water dynamics in 1) conventional flat tillage (CT); 2) R/F cultivation without PE mulched ridges (RT); and 3) R/F cultivation with PE mulched ridges (RTpm). The comparison of the simulated pressure heads during dry and wet periods revealed that the PE mulch induced significant soil moisture patterns only during the dry periods. During monsoon events, the effect of the PE mulch was dependent on the soil texture and the hydraulic conductivity. Summarizing the advantages and disadvantages of the R/F cultivation with PE mulch on sloped fields, the practice was observed to have the lowest amount of drainage water, the lowest evaporation rates but also the highest surface runoff rates. Hence, PE mulching might be assessed as a tool to reduce percolating water, but it concurrently increases water contribution to the river network by surface runoff.

Zusammenfassung

Eine ausgeglichene Stickstoffzufuhr ist in intensiv bewirtschafteten Ökosystemen von großer Bedeutung, da diese ökosystemare Dienstleistungen beeinflusst. Das Ziel dieser Studie lag in der Evaluierung der Stickstoffflüsse und deren potentiellen Auswirkungen auf die Wasserqualität eines typischen landwirtschaftlich genutzten Einzugsgebiets in Südkorea.

In der ersten Studie wählten wir zwei Ansätze zur Erstellung von Stickstoff (N)-Bilanzen der 5 Hauptkulturen des Beckens. Die Brutto- und Netto-N-Bilanzen zeigten für alle 5 Kulturen deutliche N-Überschüsse an. Die geringe Differenz zwischen den Resultaten der zwei Ansätze unterstrich die dominante Stellung des Düngers wie auch des N_{min}-Vorrates im Boden als N-Input-Quelle. Da die Düngeraufbringung den größten Anteil (>50%) an den Gesamt-N-Eingaben trug, stellt dessen Reduzierung den besten Handlungsspielraum dar, um N-Überschüsse zu reduzieren. Eine eng verknüpfte Maßnahme stellt zudem dessen Synchronisierung mit dem N_{min}-Vorrat im Boden dar. Der große Anteil des N-Düngers (>60%), der vor der Aussaat aufgebracht wird, offenbarte das Potenzial von Mehrfachapplikationen, um N-Überschuss zu reduzieren und gleichzeitig die geringen N-Nutzeffizienzen (NUE) zu erhöhen. Basierend auf den signifikanten Unterschieden zwischen Brutto- und Netto-N-Überschüssen auf Reis- und Bohnenfeldern identifizierten wir den hohen Anteil an Ernteresten (>100 kg N ha^{-1}), der auf den Feldern verbleibt, als eine weitere Maßnahme für N-Einsparungen. Mehr als 80% des Gesamt-N-Überschusses (>400 t) geht auf die 5 Hauptanbaupflanzen zurück, obwohl diese nur einen Flächenanteil von ca. 20% aufwiesen. Ein Landnutzungswechsel hin zu mehrjährigen Pflanzen mit geringeren N-Inputs wurde anhand der Hochskalierung als mögliche, wenn auch räumlich eingeschränkte, Handlung zur Reduzierung der N-Überschüsse identifiziert. Der Vergleich des Gesamt-N-Überschusses mit dem N-Export durch den einzigen Beckenabfluss zeigte, dass 73-86% des N-Überschusses durch Auswaschung und Oberflächenabfluss in die Gewässer des Einzugsgebietes transportiert wurde.

In der zweiten Studie wurde der Weg des ^{15}N-markierten Düngers in einem typischen Dammanbausystem (R/F-Anbau) mit Polyethylen (PE)-Folie verfolgt. Die N-Auswaschung wurde mit dem Model Hydrus 2D simuliert. Der Vergleich der 4 N-Düngeraten (0, 150, 250 und 350 kg N ha^{-1}) zeigte, dass bereits 150 kg N ha^{-1} ausreichten, um eine maximale Ernte zu garantieren. Aufgrund der geringen Düngernutzeffizienz (FNUE) empfehlen wir jedoch den Dünger in 3 Raten aufzubringen. Eine geringe Applikation vor der Aussaat, eine zweite nach ca. 15 Tagen und eine dritte nach ca. 50 Tagen. Jedoch muss beachtet werden, dass dies technisches Equipment zur Düngeraufbringung unter der Folie erforderlich macht. Resultierend

aus dem Ergebnis, dass die ^{15}N-Retention im Boden sowie die Nitratkonzentration im Sickerwasser ähnliche Abnahmen für die Dämme und die Gräben zeigten, folgern wir, dass die PE-Folie keine signifikanten Einflüsse auf diese zwei Faktoren aufwies und der N-Dünger in den Dämmen nicht effektiv vor Auswaschung geschützt wurde. Basierend auf der Simulation stellten wir fest, dass die Dämme und die Gräben ähnliche Summen zur Gesamt-N-Auswaschung beitrugen. Zusätzlich wurde beobachtet, dass die N-Auswaschung mit steigender N-Düngerate linear zunahm. Diese Zunahme ist für R/F-Anbausysteme ohne PE-Folie typisch. Daher schlussfolgern wir, dass die PE-Folie eine lineare Zunahme der N-Auswaschung nicht verhindern konnte und dass ohne zusätzliche Maßnahmen, wie Mehrfachaufbringung des Düngers, die PE-Folie in monsunbeeinflussten Gebieten keine positive Wirkung auf die N-Auswaschung besitzt.

In der dritten Studie wurde zuerst die Bodenwasserdynamik im Feld gemessen, um anhand dieser Daten den Einfluss der PE-Folie auf die Bodenwasserflüsse mit dem Model Hydrus 2D zu simulieren. Der Einfluss der Folie wurde anhand des Vergleichs von R/F-Anbau mit und ohne Folie und Anbau auf flachen Feldern untersucht. Der Vergleich der simulierten Druckhöhen während einer Trockenphase und während eines Regenereignisses zeigte, dass die PE-Folie signifikante Einflüsse auf die Bodenwasserflüsse nur während der Trockenphase aufwies. Durch die vollständige Sättigung bei Starkregenereignissen konnte im Gegensatz dazu kein Einfluss der Folie während Monsunereignissen festgestellt werden. Zusammenfassend lässt sich sagen, dass Dammfolienanbau auf Feldern mit Hangneigung die niedrigste Sickerwasserrate, die niedrigste Evaporationsrate, aber den höchsten Oberflächenabfluss aufwies. Demnach, kann die Dammfolie zwar durchaus als Maßnahme zur Sickerwasserreduzierung angesehen werden, erhöht aber gleichzeitig den Oberflächenabfluss in die Fließgewässer.

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List of Abbreviations

Abbreviation	Meaning
AFI	Alternate Furrow Irrigation
Ag	Silver
ANI	Added N interaction effect
Ba	Barium
BC	Biochar
BD	Bulk density
Be	Beryllium
BNF	Biological N fixation
Br	Bromine
C	Carbon
Ca	Calcium
CEC	Cationic exchange capacity
Cl	Chlorine
C_{org}	Organic carbon
CT	Conventional (flat) tillage
DFG	Deutsche Forschungsgemeinschaft
DM	Dry matter
DMZ	Demilitarized Zone
DON	Dissolved organic N
EA-IRMS coupling	Element analyzer coupled with an isotope mass spectrometer through an open split interface
EC	Electrical conductivity
EFI	Every Furrow irrigation
F	Iron
FDR	Frequent Domain Reflectometry
FNUE	Fertilizer N use efficiency
FW	Fresh weight of biomass

H	Hydrogen
HCl	Hydrochloric acid
I	Iodine
ITNI	Integrated Total Nitrogen Input
K	Potassium
KCl	Potassium chloride
K_{sat}	Saturated hydraulic conductivity
Li	Lithium
M	Molarity
MG	Megagram
Mg	Magnesium
N	Nitrogen
N2	N gas, molecular N
Na	Sodium
NaOH	Sodium hydroxide
NH_3	Ammonia
NH_4	Ammonium
N_{min}	Mineralized (inorganic) N available in soils
NO	Nitric oxide
NO_2	Nitrite
NO_3	Nitrate
NO_x	Generic term for mono-nitrogen oxides (NO, NO_2)
Nr	Reactive N
NSE	Nash-Sutcliffe efficiency
N_{tot}	Total N
NUE	N use efficiency
O	Oxygen
Oa	Horizon with well decomposed litter
Oe	Horizon with partially decomposed litter
OH	Hydroxyl group

Oi	Horizon with undecomposed plant debris
OM	Organic Matter
P	Phosphorus
PAM	Polyacrylamide
PE mulch	Polyethylene mulch
PVC	Polyvinyl chloride
R	Pearson's correlation coefficient
R^2	Coefficient of determination
Rb	Rubidium
RDA	Rural Development Administration of Korea
R/F cultivation	Ridge and furrow cultivation
RFRH	Ridge and furrow rainwater harvesting
RIG	Research Institute of Gangwon Province in Korea
RT	Ridge tillage
RTpm	Ridge tillage with PE mulch
SA	Selected-input approach
SE	Standard error of the mean
SI	Sprinkler irrigation
Sn	Tin
SOM	Soil organic matter
STDV	Standard deviation of the mean
TA	Total-input approach
TERRECO	Complex Terrain and Ecological Heterogeneity
Tg	Teragram
WHO	World Health Organization
WUE	Water use efficiency

Chapter 1 Extended Summary

1 Introduction

1.1 Framework of the research work: TERRECO

This thesis was embedded in the consortium project TERRECO (Complex Terrain and Ecological Heterogeneity) (DFG GRK 1565/1), which is dedicated to proactive capacity-building that allows to responsibly set regional goals for ecosystem service outputs. Ecosystem services are the benefits that people obtain from natural or managed ecosystems and that contribute to quality of human life and human well-being. These include provisioning services such as food and water, supporting services such as nutrient cycling, and cultural as well as regulating services (Millennium Ecosystem Assessment, 2005a). Agricultural practices can reduce the ability of ecosystems to provide such benefits. Excessive fertilization interferes with the natural nitrogen (N) cycle and can increase groundwater and surface water contamination, incurring health and water purification costs. While the supply of agricultural products is essential to humankind, many agricultural practices have inadvertent, detrimental impacts on the environment and on ecosystem services (Tilman et al., 2002).

This study was conducted in complex terrain within the Soyang Lake watershed in South Korea, the country's largest drinking water reservoir, which is known as a hot spot of agricultural non-point source pollution. 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). There is a need to quantitatively understand, to investigate current, and to address future natural resource use within complex terrain in general and the Soyang Lake watershed in particular. TERRECO applies a transdisciplinary approach, which merges the results of studies of soil processes, hydrology and water yield, nutrient transport and water quality, agricultural production, production-related biodiversity and economic gains and losses of farmers. The project focuses on understanding the flow of water via alternate pathways through the landscape, the influence of agricultural land use and intensification on the water quality, the social structures that determine land use, and the total gain or relative loss in ecosystem services associated with water use that may occur due to climate, land use, human population and social change. The aim of the project is to determine management principles that contribute to more sustainable agricultural practices both in Korea and at other complex terrains worldwide. To get a comprehensive understanding of N cycling and N fluxes and its effect on ecosystem services, especially crop production and water quality, in the study area of Haean Catchment, this study was closely linked to other studies within TERRECO such as soil hydrology, catchment hydrology, and greenhouse gas emissions.

1.2 Object of research

1.2.1 Nitrogen dynamics and budgets in agroecosystems

N is required by plants in the largest quantity and is most frequently the limiting factor in crop productivity (Fargaśová and Toelgyessy, 1993). In the absence of human activities, the natural N cycle was closed because the biggest portion of the N, primarily fixed by biological N fixation (BNF), was denitrified either in soil, sediment, or groundwater environments. There was only little redistribution and little accumulation of reactive N (Nr, defined as N bonded to C, O, or H) (Figure 1) (Galloway, 1998; Galloway et al., 2004). However, this natural N cycle was altered extraordinarily by human activities such as fossil fuel combustion and agriculture (Figure 1+2) and total N inputs to the global N cycle have approximately doubled in the last two centuries (Millennium Ecosystem Assessment, 2005b). The production and application of synthetic fertilizer, the expansion of cultivation of N fixing crops, and the deposition of N containing air pollutants have together created an additional N flux of about 210 Tg year^{-1}, only part of which is denitrified (Millennium Ecosystem Assessment, 2005b). The major driver of this change is the application of fertilizer N. For instance, more than half of the synthetic fertilizer N ever used has been applied in the past 30 years. Between 1960 and 1995, global use of N fertilizer increased 7-fold and is expected to increase another 3-fold by 2050 (Kates et al., 1993; Tilman et al., 2002; Vitousek et al., 1997).

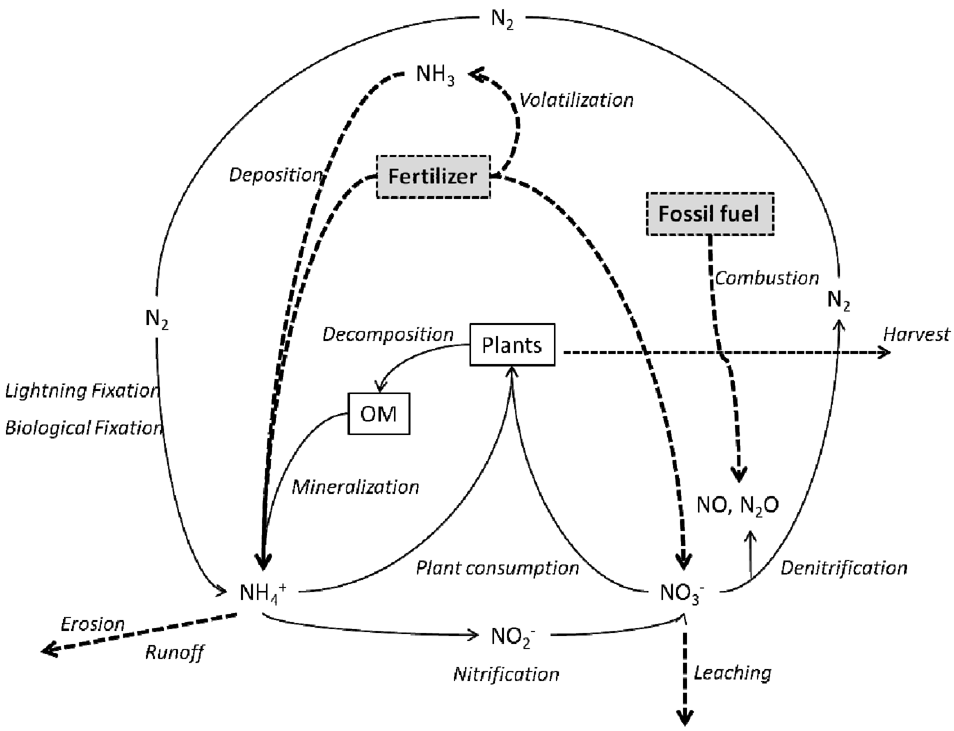

Figure 1 Simplified N cycle in a natural ecosystem in the absence of human activity. The bold and dotted arrows and boxes show the human intervention and the impact of human activities on the N cycle

Agroecosystems receive around 75% of the Nr created by human action. But as the annual amount of N accumulated in agricultural soils is small compared to the annual N amount applied, Galloway et al. (2004) suggest that >75% of the applied N is removed or transported to other environmental compartments. This low rate of N accumulation in soils is supported by Smil (1999) and Van Breemen et al. (2002). N is removed in parts from the system with crop uptake and harvest for one, but crop N uptake efficiency amounts often only to 30-50% of the applied N (Tilman et al., 2002). The significant amount of N surplus is therefore transported to the atmosphere or into the aquatic systems with processes such as leaching, emissions or surface runoff (Galloway et al., 2004; Howarth, 2004). Although most N inputs serve the agricultural production, which is essential to humankind, excessive N inputs to arable land above crop needs have detrimental impacts on the environment and result in serious environmental problems because Nr can easily move among the different media of air, soil and water (Tilman et al., 2002; UNEP, 2007; Vitousek et al., 1997). A common effect and problem of the overfertilization is the heavy non-point pollution of surface and groundwater (Zhang et al. 1996; Cherry et. al. 2008).

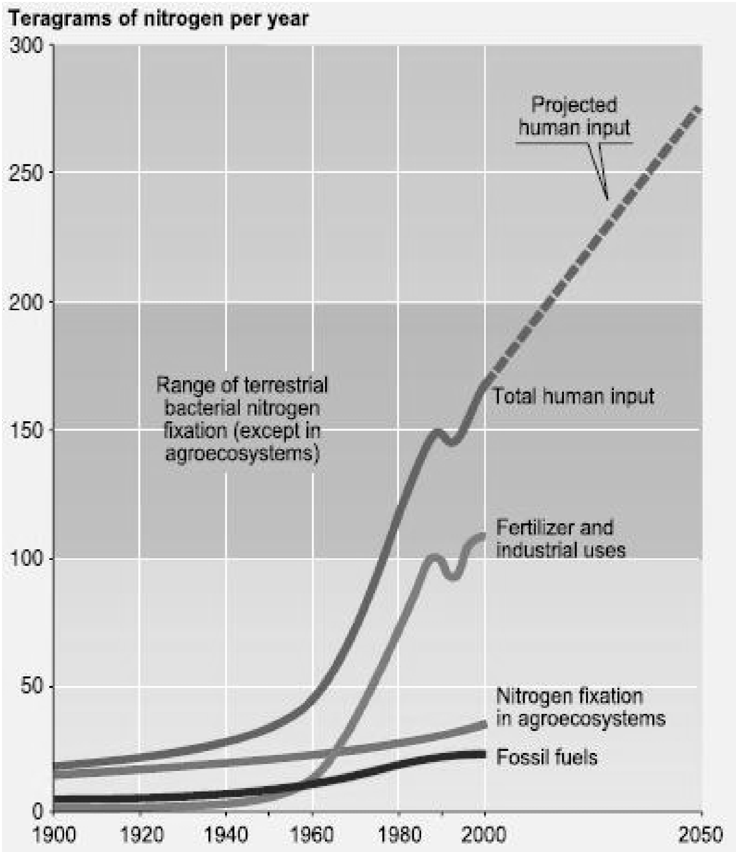

Figure 2 Global trends in the creation of Nr by human activity (Millennium Ecosystem Assessment, 2005a)

Achieving a balance between N input and N output within an agricultural-based system is therefore critical to ensure both short-term productivity and long-term sustainability (Richter and Roelcke, 2000; Watson et al., 2002). N budgets are an accepted and commonly used tool in environmental studies to relate N inputs into soil to N outputs and have been reviewed by a number of authors (Watson and Atkinson, 1999; Watson et al., 2002; Cherry et al., 2008; Oenema et al., 2003). The existing methodologies are applicable from plot to national scale but are often difficult to compare due to their flexibility in system boundaries and input sources (Cherry et al., 2008; Watson et al., 2002). Generally, 3 different budget approaches can be distinguished, which differ mainly in their determination of system boundaries, in their consideration of input and output sources as well as of internal flows. Farm gate budgets are fairly simple budgets, which quantify bought and sold N that enter and leave the farm gate with no consideration of internal transfers or loss processes (Cherry et al., 2008; Watson and Atkinson, 1999). Surface budgets consider the difference between N inputs and N outputs with crop removal and/or with animal offtake. These budgets include uncontrollable N inputs but do not usually provide information on the fate or origin of any budget surplus N (Watson et al., 2002). Soil system budgets, however, include all N inputs and N losses and therewith provide a detailed understanding of N fate (Cherry et al., 2008). Environmental studies using budget approaches have been conducted in numerous countries, in different agricultural systems, and at different scales (Table 1).

Although 70% of South Korea is characterized as mountainous (Bashkin et al., 2002), and there a thousands of small mountainous watersheds, there is no detailed N budget at the field or catchment scale for these mountainous regions. Additionally, South Korea’s agriculture is greatly influenced by heavy rainfall events during the growing season, but the N budgets found in the literature were mostly conducted in irrigated agriculture, where natural rainfall did not play an important role. N budgets for a summer monsoonal climate with heavy rainfall events (>70mm) were not found in the literature. In our study, we chose a combination of the surface budget approach and the soil system budget approach to identify possible knowledge gaps in the N cycling, to estimate N losses quantitatively, and to make more sustainable agricultural management recommendations. We used the surface budget approach but additionally tried to include estimates of N mineralization from SOM (soil organic matter) and soil N_{min} values at the beginning of the growing season. We also tried to estimate N losses with surface runoff and leaching. To be able to estimate these N loss pathways, we extrapolated the results of the field scale to the catchment scale and compared the N surplus to the stream N export. Our study area, Haean Catchment, is most suitable for such up scaling approaches and comparisons because it is a small mountainous watershed with typical characteristics of South Korea's agriculture and topography but has only one catchment outlet, in which the N is exported to the Soyang Lake.

Table 1 Compilation of published studies using nutrient budget approaches

Author	Country	System	Scale	Time step	Nutrient	N budget (kg ha^{-1})
Bashkin et al. 2002	South Korea	Agricultural landscape	Country	Year	N	+ 296
Brouwer 1998	Netherlands	Arable farm, dairy farm	Farm	Year	N	Arable: + 187 Dairy: + 407
Goulding et al. 2000	UK	Organic horticulture	Farm	Year	NPK	+ 96
Haas et al. 2007	Germany	Organic dairy farm	Farm	Year	N	+ 43
Richter and Roelcke 2000	China	Rice-wheat rotation	Field	Year	N	+ 217-335
Van Beek et al. 2003	Netherlands	Dairy farm	Farm	Year	NP	+ 213-271
Watson and Atkinson 1999	UK	Beef system	Farm	Year	NPK	+ 103-212
Zhao et al. 2006	China	Wheat-Maize rotation	Field	Year	N	+ 201-559

1.2.2 Water flow and N leaching in agricultural fields with ridges and furrows

The ridge and furrow (R/F) cultivation is an ancient agricultural practice with origins in the arid and semi-arid tropics (Lal, 1991). Today, modern R/F cultivation is a practice widely used throughout the world with many different modifications but with the ridges in common. Row crops such as maize *(Zea mays* L.), soybean *(Glycine max* (L.) Merr.), and sorghum (*Sorghum bicolor* (L.) Moench) as well as root crops that would be damaged by inundation are commonly cultivated in R/F systems. Finally, crops like potatoes (*Solanum tuberosum*)) and asparagus (*Asparagus officinalis* L.) are cultivated on ridges to ease the harvesting. The basic system of cultivation on ridges consists of an elevated ridge, which serves as the planting zone and a furrow, which serves as the infiltration zone (Figure 3). The main objectives of the ridge planting are to improve the plant root environment and to protect the crops against decay due to water logging during wet periods or during heavy rainfall (Benjamin et al., 1990; Leistra and Boesten, 2010a). The ridges improve the soil environment for seed germination, early crop emergence and growth because of warmer soil temperatures in cool and/or wet spring climates (Krause et al., 2008). The warming combined with the better drainage and aeration of the soils allows the ridges to dry out sooner than flat fields and extends the growing season (Jaynes and Swan, 1999; Leistra and Boesten, 2010a). The most important difference of R/F cultivation compared to the flat surface land use systems is the complete change of water infiltration and water fluxes in soils and on the soil surface.

Several studies proved experimentally that infiltration and initial water movement occurred largely in the furrows mainly due to surface runoff (Table 2). For example, Bargar et al. (1999) indicated this by a more rapid increase in soil water content for furrow than for equivalent ridge positions at soil depths < 45 cm in uncropped fields under natural rain. Hamlett et al. (1990) additionally observed ponding of water in the furrows, when rainfall exceeded infiltration capacity. Li et al. (2000) compared runoff from bare ridges to runoff from polyethylene (PE) mulched ridges. Runoff from the latter showed 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. Also often investigated by the listed studies was the subsequent movement of the infiltrating water in the soil. Bargar et al. (1999) indicated that the main infiltration and downward water movement occurred in the furrows, but was followed by delayed lateral and radial movements to the uncropped ridge positions. Lateral flow from the furrows to the ridges was also measured by Waddell and Weil (2006) for cropped ridges due to a negative hydraulic gradient. In contrast, Hamlett et al. (1990), Starr et al. (2005) and Kung (1990) found only little or no indication of a lateral flow directed from the furrows to the ridges in uncropped ridges and potato ridges, respectively. Starr et al. (2005) even found that sprinkler irrigation did not reach the center of the ridges, even at comparatively high precipitation rates.

Table 2 Compilation of published studies about water flow in R/F cultivation

Author	R/F configuration	Crop	Main infiltration in furrow	Vertical/horizontal water movement	Wetting of ridge	Stemflow, water repellency
Bargar et al. 1999	Permanent Ridge height: 8-11cm Spacing: 76-97cm	Uncropped	+	Vertical dominant/ Delayed lateral		Soil sealing
Hamlett et al. 1990	Temporary Spacing: 76cm	Uncropped	+ (water ponding)	Vertical dominant/ Only little lateral		
Waddell and Weil 2006	Permanent	Corn	+ (before crop emergence and after harvest)	Vertical dominant/ Lateral movement during midseason	Dry ridge tops	Stemflow
Cooley et al. 2007	Temporary Ridge height: 15cm Spacing: 90cm	Potato	+		Dry zone in center	Hydrophobic soil, Stemflow
Robinson 1999	Temporary Ridge height: 20cm Spacing: 75cm	Potato	+ (amplified by water repellent soil)		Dry zone in center	Water repellency, Stemflow
Starr et al. 2005	Temporary	Potato	+	Vertical/x	Wetted poorly	

Based on this literature review, we conclude that water flow in R/F cultivation was rarely investigated in field studies, but the number of modeling studies of the same topic is even less. Modeling studies as well as field studies about R/F cultivations with PE mulched ridges were not found at all. However, as Li et al. (2000) showed PE mulch changes drastically the surface water flow, we hypothesized that the PE mulch greatly increases the amount of surface run off, especially at sloped fields in mountainous agricultural areas. The cited field studies about surface and subsurface water flow mostly investigated the effect of the R/F cultivation system on water flow in irrigated agriculture. Surface and subsurface water flow was only seldom investigated for natural rainfall and never investigated for extreme rainfall events (>70mm) during the growing season. However, R/F cultivation with plastic mulch, intensive agriculture in mountainous areas, and summer monsoonal climates with heavy rainfall during the growing season are typical factors of the agriculture in large parts of East Asia. Therefore, we used a field monitoring network of tensiometers and FDR (Frequent Domain Reflectometry) sensors to measure soil water contents and soil water potential in sloped fields of the mountainous Haean basin and based on this data set we afterwards carried out an inverse simulation of water flow using Hydrus 2/3D. The model allowed us to investigate the influence of the PE mulch on surface and subsurface water flow during monsoonal events and during dry periods of the growing season. The comparison of simulations of R/F cultivation with PE mulch (RT_{pm}), R/F cultivation without PE mulch (RT), and flat cultivation (CT) was used to allow a better understanding of the changes of soil water dynamics and water movement induced by the PE mulch.

Leaching of nutrients and other agrochemicals, which are susceptible to percolation, is strongly associated with water infiltration and subsequent water distribution. Bolton et al. (1970) found that the volume of water that flowed through the soil was the predominant factor responsible for N loss. Nitrate (NO_3^-) is readily leached through soil and it was previously shown that NO_3^- leaching depends on various 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 processes in various crop systems with a relatively homogenous spatial distribution of water and NO_3^- have been measured using different methods (Di and Cameron 2002; Nyamangara et al. 2003; Zotarelli et al. 2007). Field studies in R/F cultivation systems with a heterogeneous distribution of water and NO_3^- are considerably less in number and have shown varied results regarding the leaching of agrochemicals in R/F cultivation compared to other tillage systems. While some studies have shown a potential for an increased leaching through the soil (Kramer et al., 1990; Kanwar et al., 1991), other studies have shown that R/F cultivation reduced downward movement of agrochemicals compared to other tillage systems (Drury et al. 1993; Hatfield et al., 1998). However, several studies observed a deeper or increased movement of agrochemicals in furrow soil compared to ridge soil due to localized water flow (Table 3). Computer simulations by Leistra and Boesten (2010b) showed that bromide leached earlier, faster, and at higher concentrations from the furrows than from the ridges. Gaynor et al. (1987) also indicated deeper percolation in furrow zones. To reduce the potential of leaching in R/F cultivations, some studies suggest isolating the agrochemicals from the infiltrating and percolating water by placing them precisely into the ridges, where the irrigation water or rainfall bypasses the agrochemical due to increased furrow infiltration. Hamlett et al. (1990) demonstrated for uncropped R/F cultivations that the total NO_3^- movement was reduced at 3 different amounts of rainfall, when NO_3^- was placed in the ridges. However, with increasing rain amounts, the downward movement of NO_3^- in the ridge increased as well and the amount of NO_3^- at the point of application concurrently decreased. Waddell and Weil (2006) also found a better uptake of agrochemicals for ridge-applied chemicals than for furrow-applied chemicals. However, their findings imply that stemflow might increase the rain infiltration into the ridge and increase the potential of solute leaching in the ridges compared to furrow application.

Table 3 Compilation of published studies about leaching of agrochemicals in R/F cultivation. SI = Sprinkler irrigation; EFI = each furrow irrigation; AFI = Alternate furrow irrigation

Author	**R/F configuration**	**Agrochemical and placement**	**Increased leaching in furrow**	**Reduced leaching in ridge**	**Dominant flow direction**	**Leaching potential**
Leistra and Boesten 2010b	Temporary Ridge height: 20cm Spacing: 75cm	Bromide and carbofuran; both broadcast	+ (surface transport from ridge to furrow)	+	Vertical (+surface flow)	> Flat tillage
Butters et al. 2000	Permanent Spacing: 76cm	Bromide broadcast	+ (SI) - (EFI, AFI)	- (SI) + (EFI, AFI)	Lateral (EFI, AFI) Lateral (SI)	SI > EFI = AFI
Clay et al. 1992	Permanent Ridge height: 7-8cm Spacing: 45cm	Alachlor, bromide, and calcium nitrate Banded in ridge top or furrow	+	+	Vertical	Banding on ridge top < banding in furrows
Jaynes and Swan 1999	Permanent Ridge height: 8-11cm Spacing: 76-97cm	Bromide, anionic dyes Ridge top, ridge shoulder or furrow	+ (furrow-applied)	+ (ridge-applied)	Vertical (ridges) Lateral (furrows)	Ridge placement < furrow placement
Waddell and Weil 2006	Permanent	Bromide, nitrate Banded in ridge top or furrow		- (due to stemflow)	Vertical Lateral (in midseason)	Ridge placement < furrow placement

Based on this literature review, we conclude that only a few of these field studies used an adequate tracer to follow the NO_3^- fate. Additionally, the biggest portion of the studies investigated the fate of agrochemicals only for precision placement of agrochemicals and only very few studies exist, where fertilizer was applied broadcast, which is a common practice in mountainous agricultural areas. About half of these studies were conducted in uncropped fields, although crop existence and crop type are important influencing factors for agrochemical leaching. Downward movement of substances in soil was mostly determined by sampling soil up to a depth of 2 m and analyzing the soil samples for the used substances. Only very few studies exist, which determined seepage water fluxes and NO_3^- concentrations in seepage water. None of the above described studies investigated the N fate in a R/F cultivation, in which the ridges were covered with PE mulch. And finally, field studies were seldom conducted in agricultural areas, where heavy rainfall events (>70mm) during the growing season play an important role.

In our study, we therefore used ^{15}N to precisely determine fertilizer NO_3^- fate in a radish cultivation under R/F cultivation with PE mulch cover. Fertilizer was applied broadcast and afterwards the field was plowed and the R/F cultivation system was implemented. With ridging of the field, the biggest portion of the fertilizer was, however, shifted into the ridges. The ridges were then covered with black PE mulch using a hand operated tool (Figure 3). As several studies suggest that fertilizer in the ridges is protected from leaching, we hypothesized that the PE mulch additionally protects the fertilizer accumulated in the ridges against the heavy rainfalls during the growing season, while the fertilizer accumulated in the furrows is lost to the groundwater. Accordingly, we hypothesized that the increased retention of fertilizer in the ridges increases in turn the N use efficiency (NUE) of the crops. The higher ^{15}N retention in combination with the increased ^{15}N uptake by plants was hypothesized to decrease the nitrate concentrations in the seepage water to meet the WHO water quality standards (WHO, 2011). We determined ^{15}N uptake by crops in the ridges and ^{15}N retention in soils separately for ridges and furrows to get a complete but separated picture of the fertilizer fate for both management zones. As we were not able to determine ^{15}N content in seepage water, we measured the NO_3^- concentration in seepage for ridges and furrows separately. By using measured tensiometric, climate as well as soil texture data, we simulated seepage water fluxes as well as N leaching with the numeric solute transport model Hydrus. The model allowed us to determine the fluxes for ridges and furrows separately as well as to look for the effects of the heavy rain events during the growing season on NO_3^- leaching.

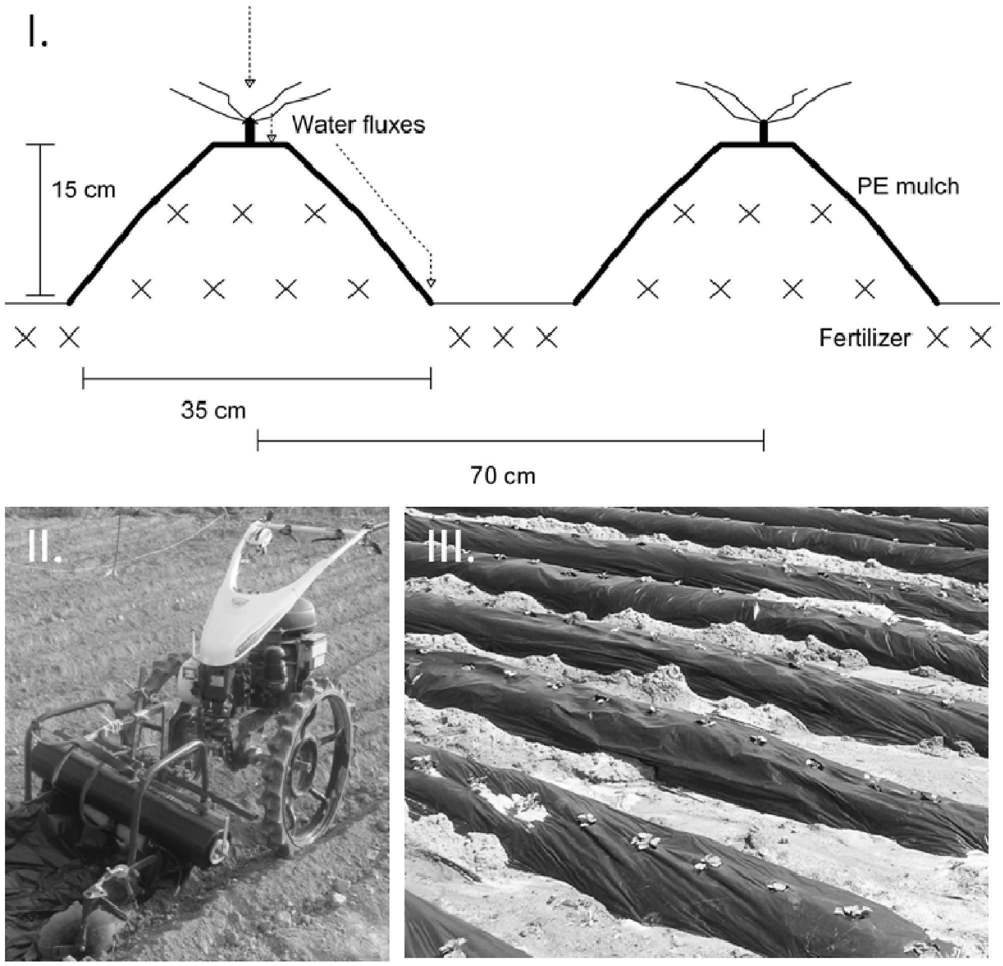

Figure 3 I. Scheme of a typical R/F cultivation with PE mulch in South Korean. Shown are the water fluxes and the distribution of broadcast applied fertilizer N after ridging process. II. Hand operated tool used for the application of the PE mulch in the study area. III. R/F cultivation in Haean Catchment, picture taken shortly after plant emergence

1.3 Objectives

We chose the mountainous basin of Haean Catchment in South Korea as our study site due to several reasons. Haean Catchment is one of the largest highland or sub-highland dryland farming areas within Soyang Lake watershed, which is known as a hot spot of agricultural non-point source pollution. The basin is further only little affected by livestock farming and not affected by industrial activities. Additionally, the landscape of the basin can be clearly separated into 3 categories: the mixed-deciduous forest vegetation belt at the rims, the dryland farming zone at the slopes, and the rice paddy area in the lowlands of the basin. The exported N from the catchment is transported with the Mandae stream to the Lake Soyang, a major drinking water reservoir in South Korea. The annual averages of rain event mean concentrations of N_{tot} (total N) in the Mandae stream were higher than observed in other streams in Korea and worldwide (Jung et al. 2009; Kim, 2006). The catchment additionally shows all typical characteristics of South Korean and East-Asian agriculture. It is characterized by typical agricultural practices of industrial countries like heavy application of fertilizer and pesticides, but at the same time it shows also characteristics of underdeveloped countries such as little use of machinery. Finally, the catchment is most suitable for studies at catchment scale because it possesses only one catchment outlet, the Mandae stream. The Mandae stream and the weather conditions of the catchment have been monitored from the Kangwon National University since several years and we were able to use some of their data sets.

The hypotheses of our first study (Chapter 2) were the following:

- Agricultural N losses during the growing season give rise to the water pollution in Haean Catchment;
- N losses were mainly related to the excessive fertilizer N inputs.

The according objectives of the first study were the following:

- To evaluate the N budget and N use efficiencies of the 5 key crops of the study area at field scale;
- To identify the potential for N surpluses as well as the potential for N savings at the field and at the catchment scale for the 5 key crops of the basin;
- To estimate N losses quantitatively and partly qualitatively;
- To develop options for a more sustainable agricultural catchment management.

A new aspect of our study is the combination of two different approaches, the surface budget approach and the soil system budget approach to confirm our hypotheses and to identify possible knowledge gaps in the N cycling. The extrapolation of field budgets to the catchment was done for several regions, but was not yet done for mountainous catchments with intensive agriculture. Additionally, no studies were found that compared the extrapolated catchment N surplus to the measured stream N export at the basin scale.

The hypotheses of our second study (Chapter 3) were:

- The applied PE mulch cover enhances the protection of the fertilizer in the ridges from the infiltrating water;
- NUE is enhanced by the protection of the fertilizer N and the increased N retention in the soil;
- The PE mulch decreases the NO_3^- concentrations in the seepage water to meet the WHO (World Health Organization) water quality standards (WHO, 2011);
- NO_3^- leaching is the main N loss pathway in a level R/F cultivation system, and
- Fertilizer N rates can be reduced without a decrease in biomass production.

The according objectives of the second study were the following:

- To follow the fate of the fertilizer N in the R/F cultivation to get an improved understanding of the effect of ridges and furrows on N fate;
- To determine the NO_3^- concentration in seepage water during the growing season;
- To simulate NO_3^- leaching losses during the growing season;
- To determine the optimal gains in ecosystem services, namely production of agricultural crops versus limited impacts on water quality.

A new aspect of this study was for one the investigation of the PE mulch on the ridges of the R/F cultivation system. Additionally, N fate in R/F cultivation systems was not yet investigated by using ^{15}N tracer. None of the existing studies determined NO_3^- concentrations in the seepage water in R/F cultivations, but only measured the NO_3^- content in soil and its respective movement in soil. Only very few modeling studies exist that investigated NO_3^- leaching in R/F cultivation systems, and no modeling study yet exits, which investigated NO_3^- leaching in a R/F cultivation with plastic mulch. Finally, another new aspect is the summer monsoonal climate with its heavy rainfall events during the growing season, which can bring more than 70 mm of precipitation per event.

The hypotheses of our third study (Chapter 4) were:

- PE mulch significantly influences the subsurface water low;
- PE mulch protects the ridge from excessive water infiltration and water logging during heavy rainfall events;
- PE mulch increases surface runoff generation during the monsoon season in sloped fields in comparison to other tillage systems;
- PE mulch subsequently decreases drainage water in the soil in sloped fields in comparison to other tillage systems.

The according objectives of the third study were the following:

- To determine the effect of PE mulch in R/F cultivation on soil water dynamics in sloped fields;
- To evaluate the soil water redistribution under a summer monsoonal climate;
- To simulate soil water dynamics under different tillage methods;
- To evaluate the simulations of the different systems for their efficiency in summer monsoon climates.

A new aspect of our third study is the PE mulch that covers the ridges. Influences of PE mulch on soil water dynamics were very rarely investigated in modeling studies. Influences of PE mulch in sloped fields with R/F cultivation were not yet investigated. Additionally, no modeling studies for R/F cultivations with PE mulch were found for summer monsoonal climates with extreme rainfall events (>70mm). Finally, no comparison of soil water dynamics of different tillage systems for summer monsoonal climates was found in the literature.

1.4 Listing of additional experimental work in the period 2009-2011

In 2009, I took part in an integrated experiment, which dealt with runoff plots on sloped field sites under R/F cultivation with PE mulch. The idea of the experiment was to combine studies about surface runoff and soil erosion (Project WP2-07), subsurface flows and water infiltration (WP2-10), and N fate and biomass production (WP2-05; this project) on sloped field sites managed with different soil additives. As soil additives, we used polyacrylamide (PAM), Biochar (BC), and a mixture of PAM and BC. The fate of the fertilizer N in the different soil treatments was followed with ^{15}N tracer. For my part of the experiment, ^{15}N uptake in crops, ^{15}N retention in soils, ^{15}N content in the sediment transported with the surface runoff, and biomass production was measured in the growing season 2009. The run off plots were set up in 3 different radish field sites located in the Haean Catchment. The hypothesis of the integrated study was that soil treatments improve farmland productivity of sloped field sites by

- Decreasing surface runoff and soil erosion;
- Increasing soil hydraulic conditions (infiltration and water retention);
- Increasing N availability, NUE and biomass production.

However, the data of this experiment was not included in this thesis due to several problems with the experimental setup, which led to biased data. The runoff plots were too small and the walls of the runoff plot influenced the plant growth and the water flow. Further, the sampling procedure and the measurements disturbed the soil conditions and damaged the PE mulch. Moreover, the tanks for the runoff collection were too small for the extreme rain events in 2009 and the setup of the runoff plots forced the surface water to flow in plot direction and created therefore artificial flow paths. Finally, the soil additives were not appropriately incorporated into the soil but only applied to the surface and were therefore partly washed away with the first heavy rain events. The design of the runoff plots was revised after the experiment in 2009 and the problems were eliminated in the 2010 experiment. However, because of the different experiment design and layout in 2010 I did not take part in the following experiment.

In 2010, I conducted an experiment to determine the atmospheric N deposition of the Haean Catchment during the 2010 growing season from June to September.

Therefore, 4 positions within the Haean Catchment were chosen: a forest site at the rims of the basin, a dryland field site as well as a rice paddy in the lowlands of the basin, and a forest site in the lowlands of the basin. The measurements were carried out following the principle of the ITNI (Integrated Total Nitrogen Input) system, which is based on the ^{15}N isotope dilution method (Russow et al., 2001). By using the isotope dilution method, we aimed to ensure that any N losses appearing during the measurements could be calculated. However, we altered the above mentioned ITNI system. Besides low costs and easy handling, our new layout was time-saving and easily replicable. We did the experiment without plants in the sampling devices. The sampling device was a funnel filled with quartz sand. We replaced the tanks for collecting rain water surplus with an unconcealed black PVC (polyvinylchloride) tube attached to the funnel's end, which enabled the rain water to leave the system after flowing through it. The tube was equipped with two different ion exchange resins (DOWEX 1X8 for anions and DOWEX 50WX8 for cations, Dow, Midland, Michigan, USA) that filtered the rain water for NO_3^- and NH_4^+ (ammonium). This system was built to give us conclusions about the total atmospheric N deposited over the entire growing period without the necessity of collecting samples in the meantime. However, we had continuing problems with the backwash of the exchange resins and therefore the data of the described experiment was not used in this thesis. We tested the rinsing of the resins in column experiments and eluted NO_3^- and NH_4^+ loaded exchange resins with 2 M HCl (hydrochloric acid) and 2 M NaOH (sodium hydroxide), respectively. We chose HCl and NaOH based on the affinities of the respective ion exchange resin. For the cation exchange resin, the affinity was indicated as follows: H+ < Be2+ <Mg2+ <Ca2+ <Sn2+ < Ba+ < Li+ < Na+ < NH4+ < K+ < Rb+ < Ag+. For the anion exchange resin the affinity was indicated as following: F- < OH- < acetate < Cl- < Br- < NO3- < I-. However, the backwash with HCl and NaOH did not completely rinse out the applied loadings. We used different approaches to obtain a better backwash, such as higher molarities of the regenerant, different flow rates of the regenerant through the columns, and different regenerants. None of the above listed approaches, however, led to a reliable method to rinse out the loadings of the exchange resins.

1.5 Study area

1.5.1 South Korea

South Korea lies between 126° East (E) – 130° East and 34° North – 38° North at the southern half of the Korean Peninsula in East Asia. It covers an area of approximately 99,400 km^2. Geographically, South Korea is positioned in the mid-latitudes of the Northern hemisphere and is part of the Northern Temperate Zone of the Eastern Hemisphere with a humid, East Asian monsoonal climate. In the summer, the temperature and humidity are high, whereas the winters in Korea are cold and dry. The East-Asian monsoon climate is known as Jangma season in Korea (Kim et al., 2007). The space and time structures of the East Asian summer monsoon are distinct from the South Asian summer monsoon. In addition, typhoons are most active during the East Asian summer monsoon and they may be considered as a component of this season as they contribute substantial amounts of rainfall and have major impacts on the region (Chang, 2004). The Jangma season lasts approximately 30-40 days from late June until late July. Another short period of rainfall occurs in early September, when the monsoon front retreats back from the North. These rainfalls occur all over South Korea, and amount to more than 50% of the annual precipitation at most weather stations of the country (Kim et al., 2007). Only 5% to 10% of the annual precipitation amount falls in the winter. However, the total amount of summer monsoonal precipitation over Korea has increased in the recent decades due to a higher occurrence of heavy rainfall (≥ 30 mm d^{-1}) events and an increase in the number of heavy rainfall days (Chung et al., 2004; Ho et al., 2003). In addition, a shortening of the monsoon season was observed (Chung et al., 2004).

80% of South Korea’s terrain belongs to hilly or mountainous regions, where the altitude of the summit ranges from 300 to more than 1,000 m, characterized by dissected relief reworked by numerous erosion cycles (Bashkin et al., 2002). Forestry and agricultural land use account for over 85% of South Korea’s land use and are typically mixed in many of the thousands of rural watersheds of the country (Kim et al., 2007). Hence, farming in South Korea is mostly conducted in mountainous areas at high altitudes with moderate steep to steep slopes. Forests cover approximately 66% of the total territorial area of South Korea (Kim et al., 2008), whereas agricultural land use is with 11,762 km^2 of paddy fields and 7,693 km^2 of upland fields responsible for about 20% of the land use (KREI, 2010; Shim and Kim, 2005). Although cultivation area per farm increased from 0.93 ha in 1970 to 1.43 ha in 2005, the cultivation area per farm is still very small compared to the United States, France, the UK and Germany. The decline of cultivated land in total, however, is a trend, which was generally observed in the last 50 years in South Korea (KREI, 2010; Shim and Kim, 2005).

1.5.2 Haean Catchment

All field work was conducted in the mountainous Haean basin located between longitude 128° 5' to 128° 11' East and latitude 38° 13' to 38° 20' North in Yanggu County, Gangwon Province in the north-eastern part of South Korea (Figure 4). It is an intensively used agricultural landscape within the Soyang Lake watershed (Figure 6), which is a major drinking water source for metropolitan areas such as the city of Seoul. The elevation of the punchbowl shaped basin (64 km^2) ranges from 339 m to 1,320 m with an average slope of 28% and maximum slope of 84%. Geologically, the study area is composed of two kinds of rocks: the bedrock in the Haean basin consists of highly weathered Jurassic biotite granite at the basin bottom, surrounded by Precambrian metamorphic rocks forming mountain ridges (Jo and Park, 2010; Kwon et al., 1990).

The typical soils of the agriculturally used area of the catchment are terric cambisols (IUSS Working Group WRB, 2007). The high soil erosion loss from mountainous cropland areas induce the local farmers to use a management practice of frequently adding sandy soil to the top layer of agricultural fields to compensate for the soil loss. Because of this artificial long-term addition of sandy soil to the fields, the agricultural soils of the catchment can even be classified as anthrosols (IUSS Working Group WRB, 2007) (Table 4). The typical forest soils of the mountain slopes are dry to slightly moist brown soils and are also classified as cambisols. However, these forest soils are overlain by moder-like forest floors with a distinct Oi (undecomposed plant debris) horizon and less distinct Oe/Oa (partially decomposed litter/ well-decomposed organic matter) horizons (Jo and Park, 2010). The Haean Catchment, as the rest of South Korea, falls within the East-Asian monsoon climate (Kim et al., 2007). During the years of 1999 and 2009, the basin showed an average annual air temperature of 8.5℃ (11-year average) and an annual precipitation amount of approximately 1,577 mm (11-year average). Annual precipitation amounts ranged between 930 to 2,300 mm yr^{-1}. Maximum precipitation amounts have been as high as 50 mm hr^{-1} or up to 220 mm d^{-1}. Storms typically last for 6 hours to 2 days. 70% of the yearly precipitation amount occurred as heavy rainfall between June and August, while approximately 90% of the total precipitation amount occurred from April to October, thus, during the growing season of the catchment. Daily precipitation amounts and temperature data for the years 2009 and 2010 have been monitored with 13 and 14 weather stations (WS-GP1, Delta-T Devices, Cambridge, UK), respectively, distributed throughout the basin (Figure 5).

Table 4 Mean values of the properties of agricultural soils (0-30 cm) in the Haean Catchment. 31 fields, which were located throughout the catchment, were sampled (5 samples per field) and analyzed. The fields covered the 5 main crops of the catchment. 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

Sand	Silt	Clay	d_B	pH	SOM	EC	CEC	N_{tot}	C_{org}	N_{min}
%	*%*	*%*	*g cm^{-3}*		*g kg^{-1}*	*µS m^{-1}*	*cmol$_c$ kg^{-1}*	*%*	*%*	*kg ha^{-1}*
69	**25**	**6**	**1.23**	**5.8**	**11.7**	**0.1**	**10.6**	**0.064**	**0.63**	NO_3^-: **93**
(±2.1)	*(±1.5)*	*(±0.6)*	*(±0.1)*	*(±0.6)*	*(±0.2)*	*(±0.06)*	*(±2.9)*	*(±0.03)*	*(±0.4)*	*(±79)*
										NH_4^+: **98**
										(±47)

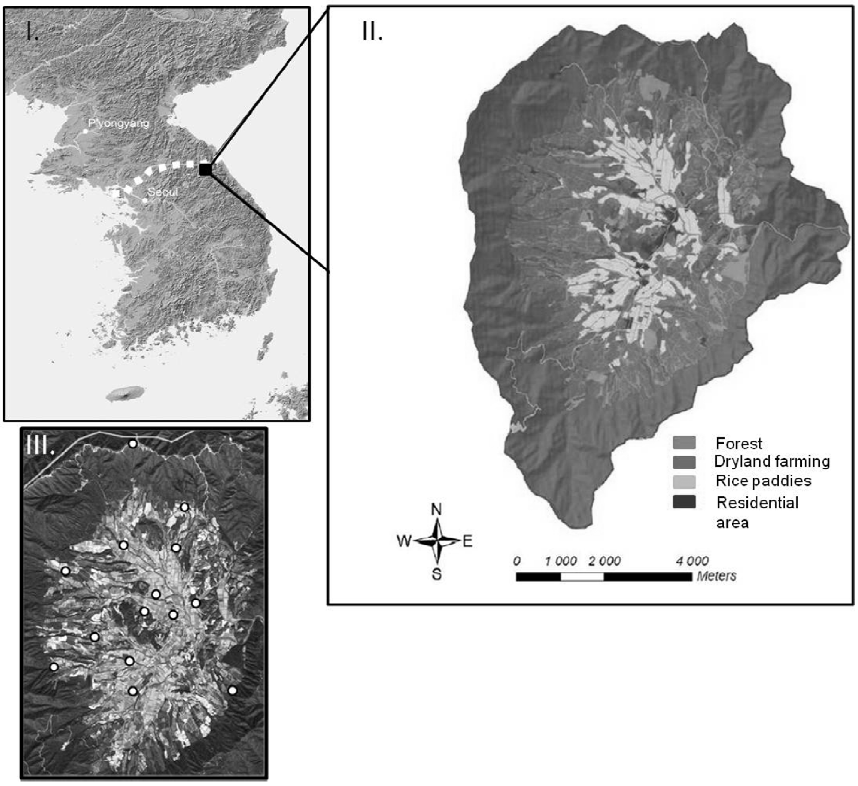

Figure 4 I. Location of the Haean Catchment in South Korea. The dotted white line marks the DMZ (Demilitarized Zone) between North Korea and South Korea. II. Land use map of the Haean Catchment. III. Locations of recording weather stations in the Haean Catchment

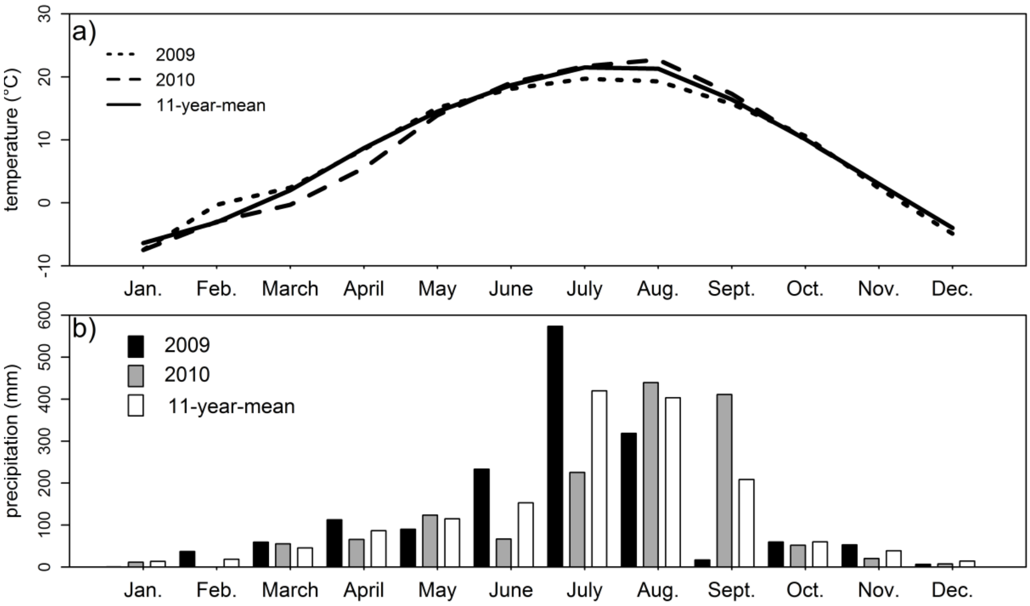

Figure 5 a) Mean daily temperature (℃), b) Mean total precipitation amount (mm) for the years 2009 and 2010 as well as the 11-year mean (1999-2009) of the Haean Catchment

The Haean basin represents one of the largest highland or sub-highland dryland farming areas in the Soyang Lake Watershed. The landscape of the basin can be divided in 3 main land use categories: the mixed-deciduous forest vegetation belt, the dryland farming zone, and the rice paddy area. In 2009, approximately 34% of the Haean Catchment was covered with agricultural land (cropland + grasslands) (Table 5). Cropland accounted for 27% of the basin. The landscape of the catchment, however, was highly fragmented because of a patchwork of small dryland fields and rice paddies. The crop, which covered the largest area in the basin, was paddy rice with 30% coverage (Yanggu County Office, 2010). In the Haean Catchment, as in the rest of South Korea, rice paddies are cultivated in flat land that is flooded annually during monsoon season, and where gravity provides plenty of water for irrigation systems (Figure 4) (Kim et al., 2007). The 4 most important dryland crops (radish, bean, potato, and cabbage) accounted for approx. 52% of the cropland in 2009 (Yanggu County Office, 2010). Dryland crops are grown on the basin slopes in ridge-cultivation systems with black polyethylene (PE) mulch, and where irrigation is difficult. However, the 5 key crops of the catchment accounted for over 80% of the cropland of the basin in 2009. Still small in size in the year 2009, but continuously and rapidly expanding within the catchment, were *Codonopsis pilosula*, ginseng, and the plantings of orchards.

The Research Institute of Gangwon (RIG) in Chuncheon has promoted a change to planting of perennial crops to stabilize soils and prevent erosion. Another driver of the recent land use change is the economic market. Therefore, this occurring land use change towards planting of perennial crops in the Haean Catchment is expected to continue in the future. Along the mountain ridges and slopes of the catchment, land is a naturally regenerating mixed deciduous forest, mainly dominated by oak species. The catchment is little affected by livestock farming and not affected by industrial activities.

The stream network, however, is well developed, and streams begin on the forested slopes and coalesce near the village of Haean-myun (Figure 6). The Mandae stream, the only outlet of the catchment, leaves the basin toward the East and subsequently south to Soyang Lake.

Table 5 Land use in the Haean Catchment in 2009. I. Total land use of the catchment. II. Agricultural crops of the catchment

I. Land use	**ha**	**%**	**II. Crops**	**ha**	**%**
Cropland	1720	27	Bean	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**

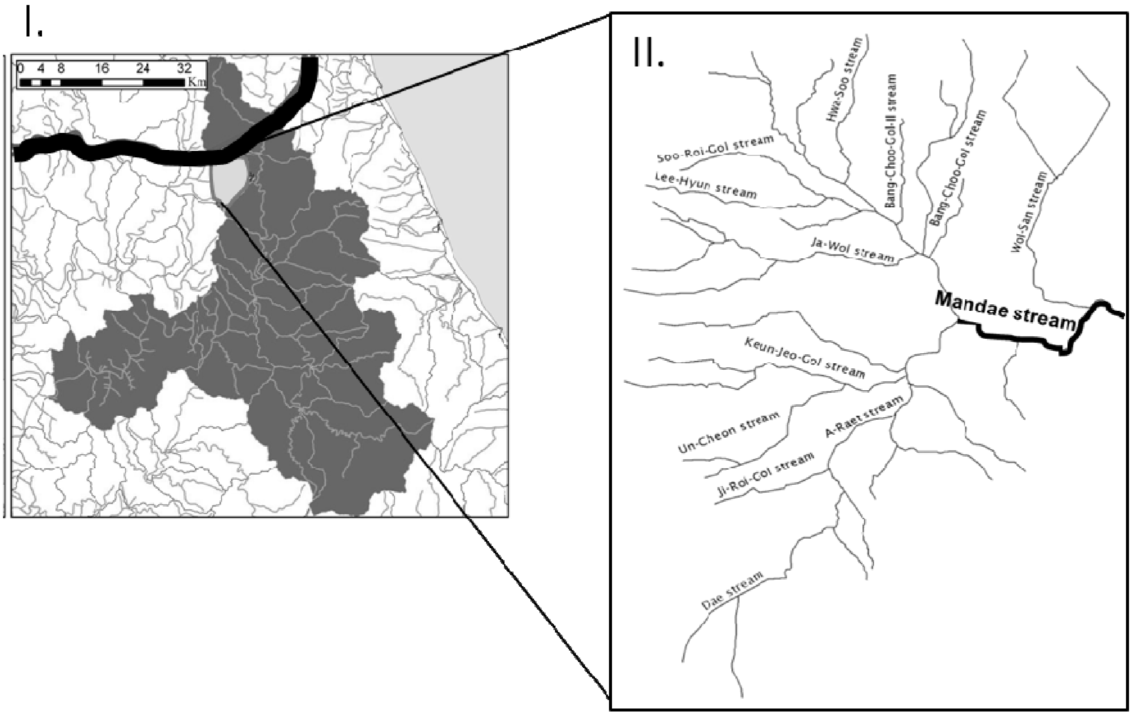

Figure 6 I. Location of Soyang Lake Watershed (dark grey) and of the Haean Catchment (light grey) within this watershed. The bold black line marks the DMZ between North Korea and South Korea. II. The stream network of the Haean Catchment. The bold black line shows the only outlet of the catchment, the Mandae stream

1.6 Synopsis

1.6.1 N use efficiency and fertilizer N use efficiency (Chapter 2+3)

Nutrient use efficiency (NUE) or fertilizer N use efficiency (FNUE) of the crops was determined in two different experiments. In the first study, we applied the N budget approach at the field and at the catchment scale. The N budget allowed us to quantify the NUE and FNUE of the 5 key crops, which cover more than 80% of the catchment's agricultural area, and to identify crops, for which high N losses can be assumed due to low NUE. Based on the 2009 study, we selected 1 of the 5 observed key crops to look at the FNUE at the plot scale in detail and to investigate its development during the 2010 growing season. In this second study, we used an approach based on the application of ^{15}N to trace the fate of the fertilizer N.

In the first study, FNUE of the crops was calculated as the amount of N exported from the field with harvest (harvest N) divided by the N input applied as fertilizer N. The NUE, however, was calculated as the amount of harvested N divided by the total N input into the system. The total N input into the system included fertilizer N, N mineralization from SOM, soil N_{min}, atmospheric deposition N, symbiotic and non-symbiotic fixation N, irrigation N as well as seed N as N input sources. This total-input approach (TA) used by Korsaeth and Eltun (2008) was compared with a second approach, the selected-input approach (SA) (LfL, 2011), which puts the N inputs from atmospheric deposition, seed, and non-symbiotic fixation on a level with the N outputs by gaseous emissions and denitrification. Thus, it excludes some N input sources in order to take potential N losses during the growing season into account. This implies that the TA calculates the maximum possible results, as in a worst-case scenario, whereas the SA tries to respect uncertainties of the simplified calculation. The information needed for the calculations was either measured or taken from the literature. We selected for each crop type 4 to 8 agricultural fields for the in situ measurements. For the soil analysis, 5 field replicates were taken from each of the 31 fields in total, whereas for the plant analysis we harvested 3 plots ($1m^2$) per agricultural field.

The results of the experiment in 2009 showed that the mean NUE for the TA was highest for the 4 dryland crops: radish (43%), bean (40%), potato (40%), and cabbage (39%). Only the NUE of rice was with 24% fairly lower ($P < 0.05$, ANOVA). Since N losses were considered in the SA, the NUE for this approach was expected to be higher for all of the 5 crops. However, the results of the NUE for the SA were found to be only slightly higher, when compared to the TA (Figure 7). Additionally, no crop type showed any effect on NUE ($P > 0.05$, ANOVA). Average crop N uptake efficiency for the TA and the SA amounted to 37% and 40%, respectively. This small difference between the NUE estimated by the two approaches indicates the strong influence of fertilizer N application on the crop systems and its dominant role as N input source. The mean FNUE increased in the order: rice (39%), cabbage (69%), radish (80%), and potato (83%), resulting in a mean fertilizer NUE of 68% for the 5 key crops of the catchment. Rice was the only crop with a significant effect on FNUE ($P < 0.05$, ANOVA). FNUE for bean was not calculated as mineral N fertilizer was not an important N source and only accounted for 8% of the N input. For both calculations, the NUE and the FNUE, no significant differences were found between the crops. This is a clear indication of the excessive mineral N fertilization at the beginning of the growing season. On average, 65% of the mineral N fertilizer was applied prior to planting, which made the biggest portion of the fertilizer vulnerable to N losses in the early phase of the growing season when the plants had not yet emerged but heavy rainfall occurred. This pattern was found for all crop types and subsequently led to the similar high N losses.

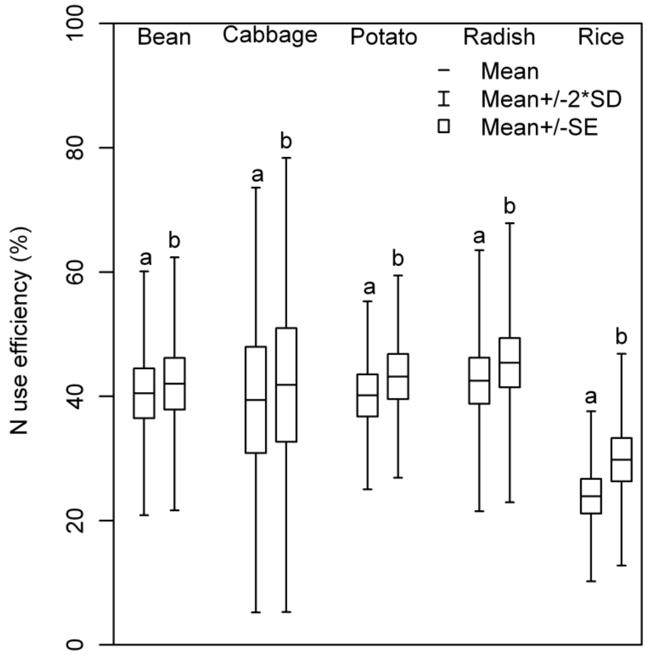

Figure 7 N use efficiencies of the 5 key crops of the Haean Catchment. a: calculated with the results of the TA ; b: calculated with the results of the SA

Our results for the mean NUE of the 5 key crops of the catchment were supported by findings from Bashkin et al. (2002), which showed that the mean NUE of crops in South Korea was with 38% the lowest in Asia. Additionally, our results of the individual NUE of the 5 crops showed also a high consistency with findings from other studies, which state a NUE of flooded rice of 20-40% in field studies and a NUE of upland crops of 40-60% (Cassmann et al., 1993; Vlek and Byrnes, 1986). However, the measured NUE in 2009 of all 5 key crops were at the lower end of these literature ranges. The performance of the applied fertilizer N depends strongly on the source and management of the fertilizer applied to an agroecosystem (Vlek and Byrnes, 1986). In Haean Catchment, we found that on average 65% of the mineral N fertilizer was applied prior to planting, which made it vulnerable to N losses at the beginning of the growing season when heavy rain events occurring and the plant had not yet emerged. Additionally, the fertilizer applied prior to planting was usually applied broadcast to the agricultural fields. Although, the following process of ridging accumulated the biggest portion of the fertilizer in the ridges, the part, which accumulated in the furrows, was quickly lost to leaching with percolating soil water. This pattern was demonstrated in the

2010 leaching experiment in a radish cultivation in Haean Catchment (Chapter 1.6.3). Besides, the applied fertilizer N rates in the Haean Catchment exceeded the recommendations given by the Rural Development Administration of South Korea (RDA) for all crops except radish and bean. In 2009, we found that the added fertilizer N rates exceeded the recommendations by 2.3-, 1.5- and 1.2-times for rice, potato and cabbage, respectively. The affordability of fertilizer N combined with the convenience of not having to apply N again during the growing season leads to excessive overapplication at the beginning of the growing season also in other parts of the world (Raun and Johnson, 1999). In our N budget study, we found clear indications that the high N losses in the summer monsoon season induced by the above described management practices were responsible for the comparatively low efficiencies of all dryland crops. Our modeling study of NO_3^- leaching losses in a radish cultivation in the Haean Catchment in 2010 showed that the biggest part of the supplied fertilizer N (>50%) percolated deeper than the root zone during the growing season and was therefore lost to groundwater. At the sloping field sites of Haean Catchment, N loss with surface runoff plays an additional role. Soil erosion measurements in the Haean Catchment in 2010 showed that more than 1 kg N ha^{-1} was transported on steep dryland fields by surface runoff during single storm events (> 70mm) (Arnhold, unpublished data). Finally, we found very high FNUE for the key crops in the Haean Catchment in 2009. A much lower FNUE, namely 27% for summer radish, was obtained from the ^{15}N labeling experiment conducted in 2010. This contrast exposes the strong impact of other N sinks and sources on the budget calculation method used in the study of 2009. The method largely overestimated FNUE and was not appropriate to quantify the efficiency with which crops take up fertilizer N.

We therefore used in the second experiment a commonly accepted and more precise method to follow the fate of fertilizer N. In the 2010 experiment, we used ^{15}N labeled fertilizer because ^{15}N isotopes are an invaluable tool to trace the movement of fertilizer N through soil/plant systems (Xu et al. 2008; Buresh et al, 1982). However, the ^{15}N isotope technique is known to underestimate the FNUE due to the so-called added N interaction (ANI) effect (Eviner et al., 2000; Hart et al., 1986; Jenkinson et al., 1985). Using $K^{15}NO_3$ (10 at%), we investigated the tracer uptake by crops at the 4 fertilizer N rates N50, N150, N250, and N350, reflecting the application of 50, 150, 250, and 350 kg NO_3^--N ha^{-1}, in a radish system in 2010. Radish was selected out of the 5 key crops for this detailed investigation of FNUE due to several reasons: 1) radish covered the largest area of all dryland crops of the catchment; 2) radish is easily harvested and separated into plant parts; and 3) it showed similar NUE to the other dryland crops. The experiment was conducted at a level field to avoid fertilizer N loss through surface runoff, which can play a considerable role at sloping fields as was shown above. The ^{15}N labeling experiment was performed in microplots (125x75 cm), each containing 6 labeled radish plants. The tracer was applied 9 days after the broadcast fertilization of the radish field. After application of the tracer, the ridges were covered with impervious black PE mulch. The process of ridging resulted in the accumulation of the biggest portion of the fertilizer in the ridges. Radishes were sown 4 days after the application of the tracer. The labeled plants were sampled and measured gravimetrically at day 25, 50, and 75 after sowing. ^{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) (EA-IRMS). The FNUE was expressed as the percentage of applied ^{15}N fertilizer taken up by the above- and below-ground plant parts.

In the 2010 study, we found that the ^{15}N uptake increased over the entire 75 days of growth only for the higher fertilizer N rates (N250, N350), while the recovery of ^{15}N in plants at N50 and N150 was highest at day 50 of growth (Figure 8). The increase in ^{15}N from day 25 to day 50 was significant at all N addition rates, whereas the increase for the last 25 days was only significant at N350. At the first sampling day, the order of the mean FNUE was as follows: 3.8% (N150) > 3.7% (N50) > 2.7% (N250) > 1.7% (N350). At day 50, the order was similar but showed an increase in FNUE for all N rates: 36% (N50) > 30% (N150) > 22% (N350) > 19% (N250). At day 75, the final FNUE ranged between 20% (N250) and 32% (N50), and this difference was found to be significant. The mean FNUE of all fertilizer N rates at final harvest was calculated to 27%.

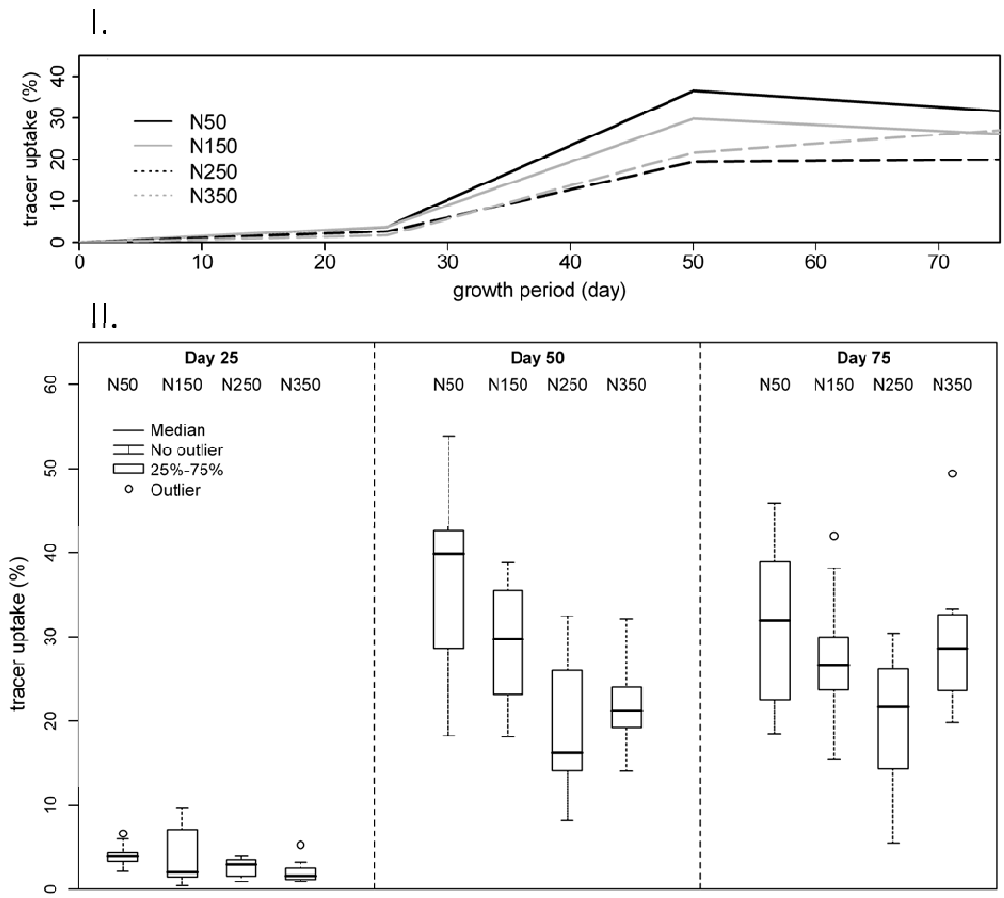

Figure 8 I. Development of the ^{15}N uptake by radish plants at the 4 fertilizer N rates from planting to harvesting; II. Statistical evaluation of the ^{15}N uptake by radish plants at the 4 fertilizer N rates for day 25, day 50, and day 75 of growth

As mentioned above, studies with ^{15}N fertilizers have often shown that fertilizer N application increased plant uptake of unlabeled soil N due to mineralization-immobilization turnover (Jenkinson et al. 1985; Kuzyakov et al. 2000). Hence, ^{15}N uptake by crops may be lower if immobilization of fertilizer N occurs to a significant extent. This pool substitution could lead to an underestimation of the fertilizer N uptake by plants (Eviner et al., 2000; Vlek and Byrnes 1986). We, however, assumed that the error in our study was low due to the low SOM content of the sandy soil. Taking a slight underestimation into account, our calculated mean FNUE in 2010 for the level radish field was still low. We identified the low FNUE of ~3% in the first 25 days of the growing season as a responsible factor for this poor performance. In the first half of these 25 days, the radish crop had not even emerged yet and the results showed that the plants were not able to utilize the available fertilizer N, which was applied prior to planting. 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. While our results showed that the tracer was increasingly utilized by the plants after day 25, some studies suggest that stemflow might enhance leaching in the ridges with crop emergence and further growth (Smelt et al., 1981, Robinson 1999, Waddell and Weil, 2006). The leaching induced by this increased water infiltration in the ridges due to stemflow together with the increased crop N uptake might be responsible for the our finding that after day 50 no significant amount of tracer was taken up by the plants at 3 out of the 4 N addition rates. These results imply that the biggest portion of the tracer was lost by day 50. This was highly consistent with the fact that we observed no significant biomass production in the last 25 days of growth at any of the 4 N addition rates (Figure 9).

To summarize and conclude our results from the 2010 study, the tracer uptake by plants from planting to day 25 was generally very low because the crops had not emerged for the first half of the 25 days. A smaller fertilizer N application prior to planting followed by a second application around day 15 could help optimize the FNUE of the first 25 days. The ^{15}N uptake at day 50 was considerably higher at the two lower N addition rates, implying higher losses of the excessive fertilizer N at the two higher rates from day 25 to 50, when stemflow-induced fertilizer N losses can be fairly substantial. However, as the tracer uptake at N350 increased significantly from day 50 to 75 but stagnated for the two lower N addition rates, the final tracer recovery in plants at the rates N50, N150, and N350 was fairly similar. This implies that a third fertilizer N application would be needed at the N addition rate N50 and N150 around day 50. As differences in biomass production were not significant, we recommend a total fertilizer N addition of 150 kg NO_3^--N ha^{-1} applied in 3 split application. This addition rate reduces the fertilizer N losses, while the biomass production is comparable with the higher N addition rates.

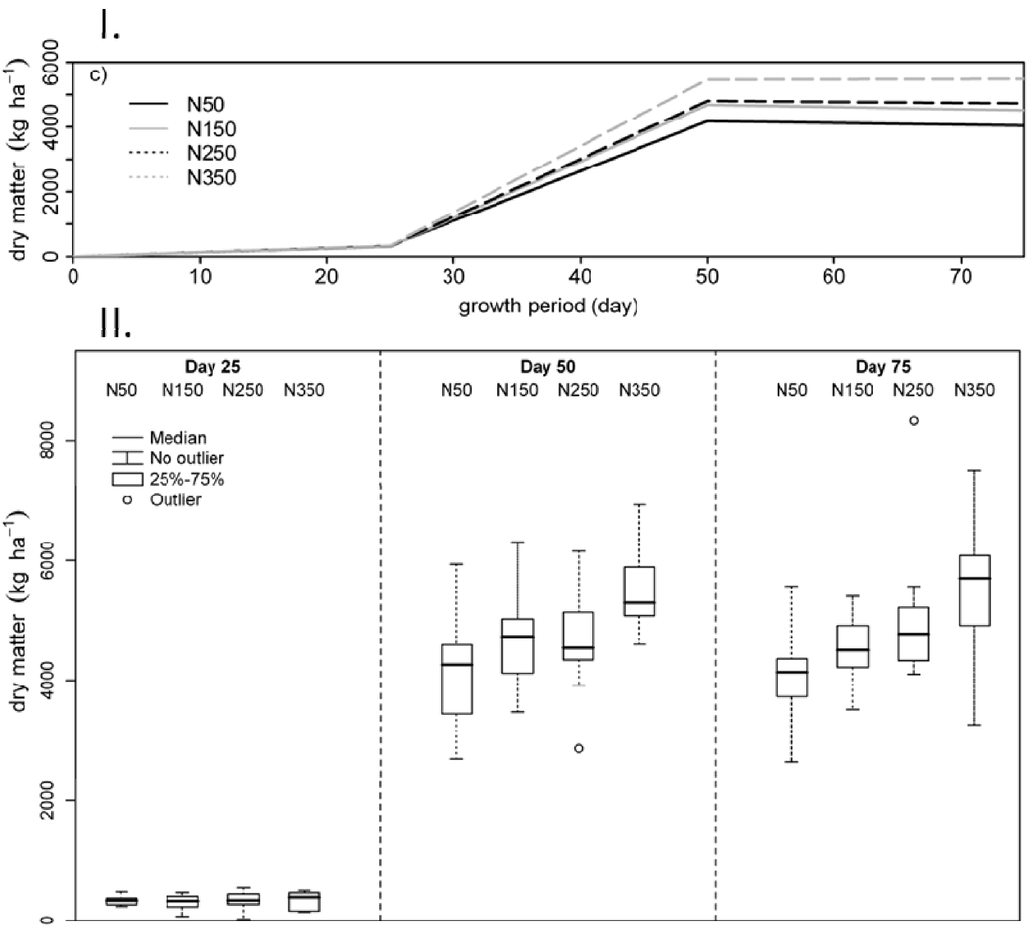

Figure 9 I. Development of the dry biomass production of the radish plants at the 4 fertilizer N rates from planting to harvesting; II. Statistical evaluation of the dry biomass production of the radish plants at the 4 fertilizer N rates for day 25, day 50, and day 75 of growth

1.6.2 N budget at field and catchment scale (Chapter 2)

To relate N inputs into soil under intensive agriculture to N outputs at field scale, we conducted a N budget analysis for the 5 key crops that cover more than 80% of the catchment's agricultural area in 2009 (see above). The field budgets were in a second step extrapolated to the catchment level to determine the contribution of the agricultural area to the N export at catchment scale. To validate the results of the upscaling process and to find possible knowledge gaps in the catchment's N fluxes, the total N export with stream water was identified in a third step. The Haean basin is most suitable for such upscaling and comparison studies due to two main reasons. It is one of the largest highland or sub-highland dryland farming areas within Soyang Lake watershed and is only little affected by livestock farming and not affected by industrial activities. Additionally, the catchment possesses only one catchment outlet, the Mandae stream, which is monitored by the Kangwon National University since several years. By using the two in chapter 1.6.1 described approaches, the amounts of gross N (N input minus crop N) and net N (N input minus harvest N) surplus were determined (Figure 10). In both approaches, we considered N mineralization from SOM and from crop residues as well as inorganic N in soils to provide detailed information on the total N budgets. The information needed for the calculations was either measured or taken from the literature. We selected for each crop type 4 to 8 agricultural fields for the in situ measurements. For the soil analysis, 5 field replicates were taken from each of the 31 fields in total, whereas for the plant analysis we harvested 3 plots ($1m^2$) per agricultural field. Monthly routine stream water sampling was conducted at the catchment outlet from January to December 2009. Daily average surface water discharge at the catchment outlet was estimated through a catchment wide spatial water balance analysis.

Our calculations of the field budgets of both approaches in 2009 pointed out gross and net N surpluses for each crop type at the end of the growing season. For the TA, only bean showed a significantly lower gross N surplus as the other 4 crops due to the considerably lower fertilizer N application (Table 6). Net N surplus at field scale for the TA was found to be highest for cabbage (325 kg N ha^{-1}) and again lowest for bean (251 kg N ha^{-1}). The comparison between gross N and net N surplus calculated with the TA revealed significant differences only for the rice and bean field budgets. The total N inputs of the TA exceeded N outputs with harvest on the average by 2.8-times. As any N accumulation in the sandy soils was measured to be insignificant in the ^{15}N experiment in 2010 (Chapter 1.6.3), these findings indicate substantial N loss in the landscape.

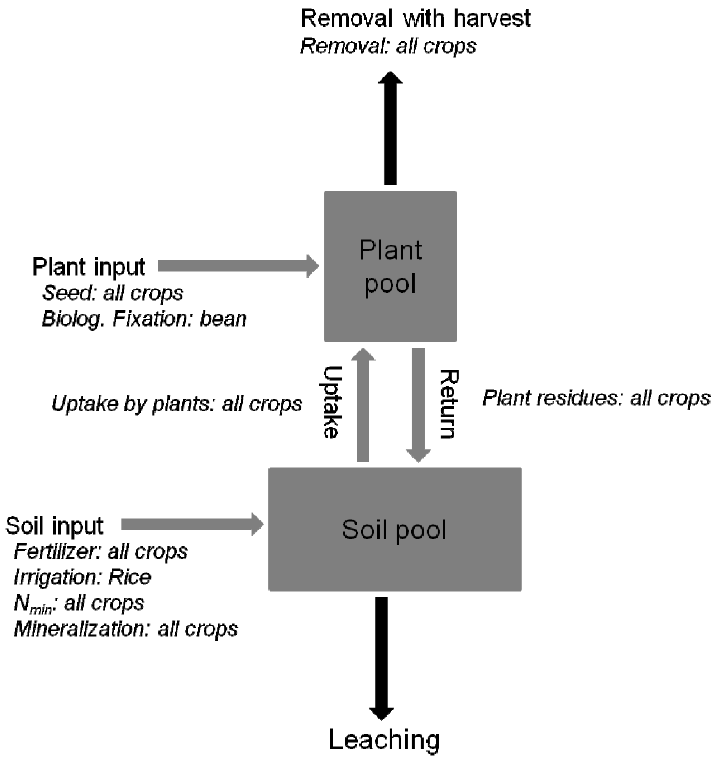

Figure 10 Scheme of N fluxes in a soil-plant-system. **TA**: N input (Fertilizer, seed, atmospheric deposition, BNF, irrigation, N_{min}, mineralization) **–** N Output (Removal with harvest); **SA**: N input (Fertilizer, irrigation, BNF, N_{min}, mineralization) **–** N Output (Removal with harvest). The latter approach excludes the underlined N input sources in order to take potential N losses during the growing season into account. This implies that the TA calculates the maximum results, whereas the SA tries to respect uncertainties of the simplified calculation

As expected, the results of the SA showed generally lower gross N and net N surpluses for all crops, but the difference between gross and net N surplus was again significant for rice and bean. These significant differences between gross N surplus and net N surplus observed for the TA and the SA were found to be related to the high amount of plant residues remaining at the bean and rice fields after harvesting (> 50%). Based on these findings, we identified the factor of remaining plant residues to offer a possible scope of action for potential N savings for bean and rice at the field scale. The remaining plant residues after the crop removal for harvest were observed to add around 100 kg N ha^{-1} to 150 kg N ha^{-1} in organic form to the net N surpluses of these two crop types. This organic N will consequently remain in the soil until its mineralization to inorganic N, after which it can be taken up by crops or is lost to other environmental compartments. An adapted management of these rice and bean plant residues could therefore play a relevant role in improving the field budgets in Haean Catchment. Studies about BC offer some feasible options for the Haean Catchment. For example, rice husks could be used for the production of BC that could be applied to any cropping system in the Haean Catchment. BC production shows therefore a potential to diminish N surpluses and at the same time it could be used as a soil amendment to enhance soil fertility and increase crop productivity (Lehmann et al., 2006; Lehmann and Rondon, 2006).

However, we also observed that the differences between the gross N and net N surpluses of the two approaches were fairly small at the field scale. This indicates the strong influence of mineral fertilizer N application as well as soil N_{min} on the crop systems and its dominant roles as N input sources. The main N input sources of rice, radish, potato, and cabbage with an average of 55% of total N input were related to the application of mineral fertilizers. Only for bean, fertilizer N did not play an important role as N input source because 43% of the total N input was related to BNF. For potato, cabbage, and rice we found that the fertilizer N applications in the Haean Catchment exceeded the fertilizer N recommendations given by the RDA by 1.5-, 1.2-, and 2.3-times, respectively. We identified these excessive N fertilizations as a second and the major possible scope of action to reduce the net N surplus at the field scale. As pointed out for radish cultivations in the Haean Catchment in chapter 1.6.1, the fertilizer recommendations given by the RDA could be even further reduced without reducing the biomass production, especially when split applications were used. On average 65% of the mineral N fertilizer in Haean Catchment was applied prior to planting, which made the biggest portion of the fertilizer vulnerable to N losses in the early phase of the growing season when the plants had not yet emerged but heavy rainfall occurred. The timing and the frequency of the fertilizer N applications need to be matched to the plants' N uptake as also shown in chapter 1.6.1. Additionally, fertilizer N and N_{min} together were on average found to be responsible for over 80% of the total N input of the 5 key crops of the Haean Catchment. N_{min} was for all crops observed to be the second biggest N input source, but the two N input sources did not seem to be matched. Fertilizer N inputs need to be adjusted to the organic and inorganic N in the soil as it is common practice in countries with intensive agriculture. Finally, the use of short-term rotational crops would also be beneficial to store excessive N and make it available at a later point in time for the successive crop. Short-term cover crops could play an important role in the Haean Catchment especially for radish, cabbage, and partly for potato, which are harvested in the mid-growing season and the fallow fields are prone to leaching and surface runoff during the following months.

Table 6 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}. [1] = total-input approach. [2] = selected-input approach

	Bean	**Cabbage**	**Potato**	**Radish**	**Rice**
	x̄/ *SE/Range*	**x̄/** *SE/Range*	**x̄/** *SE/Range*	**x̄/** *SE/Range*	**x̄/** *SE/Range*
N input:					
Fertilizer N	**33**	**296**/*-/318-274*	**210**	**254**	**234**
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**
Irrigation N	**0**	**0**	**0**	**0**	**15**
Seed N	**3**	**3**	**1.5**	**1.5**	**3**
Sum N input[1]	**422**	**520**	**433**	**477**	**382**
Sum N input[2]	**404**	**487**	**401**	**445**	**318**
N output:					
Harvest 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 N Output	**171**/*17/100-205*	**207**/*40/143-319*	**174**/*15/132-211*	**203**/*18/115-267*	**91**/*11/65-136*

In the second step, we upscaled these field N surpluses to the catchment level by using statistical data on land use in Haean Catchment (64 km^2), the calculated net N surpluses of the 5 key crops of the catchment, and literature data for other crop types and land use systems of Haean Catchment. The total catchment N surplus amounted to 473 Mg and to 403 Mg for the TA and SA, respectively. It was shown that agriculture accounted for over 90% of the N surplus at the catchment level even though its areal contribution was only 34%. The contribution of the measured 5 key crops to the catchment N surplus added up to more than 80% even though they only covered around 20% of the total area of the catchment (Figure 11). The high N surpluses at field scale of the 5 key crops are clearly responsible for their high N surpluses at the catchment scale. However, for both N budget approaches the individual contribution to the N surplus at catchment scale increased in the order cabbage < potato < bean < radish < rice. Ginseng, codonopsis, and orchards did not play a significant role in 2009 due to their lower N input and the small area they covered. In contrast, the high contribution of rice and radish at the catchment scale resulted from the high net N surpluses at the field scale as well as from the large area they covered within the catchment. To reduce their contribution, the N surpluses at field scale have to be drastically reduced by applying the above described recommendations.

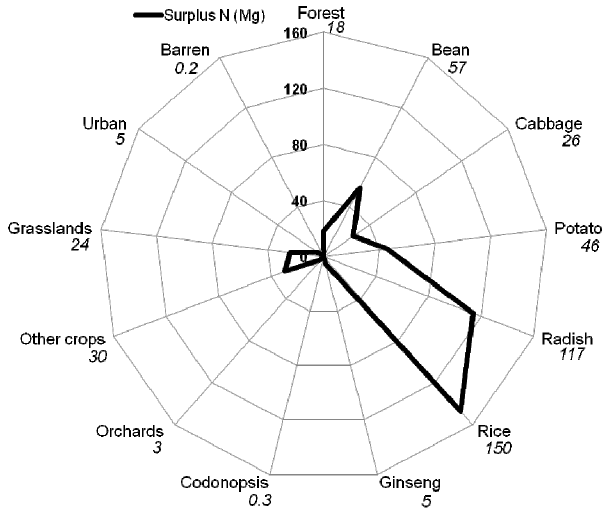

Figure 11 Net N surplus (Mg) for specific crops and non-agricultural land use categories at the catchment scale in 2009. Net N surplus was calculated with the TA. Values in *italics* give the amount of total net N surplus of each land use category

Additionally, the analysis of the catchment N budget implied that an increased cultivation of perennial crops with their fairly lower fertilizer N inputs, like ginseng and codonopsis, and a correspondingly decreased cultivation of the 5 current key crops with their high fertilizer N inputs might be a good scope of action to reduce the high N surplus found at the catchment scale. However, one has to consider that the five key crops of Haean Catchment are important parts of the Korean diet and a decrease in their production in favor of perennial crops could lead to an increasing pressure for even higher local yields and to the delocalization of the same cultivation problems to other agricultural areas. Reducing fertilizer N applications and improving plant residue management are therefore the major scopes of action, on which should be focused to reduce the agricultural contribution to the total catchment N surplus. To support the upscaled catchment level estimates, the catchment N surplus was in a third step compared with the stream N export at the catchment outlet. Stream water N in the catchment outlet amounted to 321 Mg NO_3^- and 8 Mg NH_4^+ during the growing season. This represents 73% of the agricultural N surpluses calculated with the TA and 86% of the agricultural N surplus calculated with the SA. N leaching and N loss with surface runoff to aquatic systems were therefore the dominant N loss pathways in 2009, leading to a seasonal inorganic N export of 329 Mg with the catchment outlet.

1.6.3 N leaching influenced by R/F cultivation with plastic mulch (Chapter 3)

In this study, we identified N dynamics separately for plastic-mulched ridges and bare furrows to get an improved understanding of the effect of microtopography, namely the ridges and furrows, and of the PE mulch on N fate and N losses with leaching. We additionally investigated the fate of the fertilizer N for different fertilizer N rates with the goal of developing more sustainable agricultural practices with optimal gains, namely crop production versus limited impacts on water quality. Using $K^{15}NO_3$ (10 at%), we investigated the tracer recovery in soils and plants and the tracer losses with leaching at the 4 fertilizer N rates N50, N150, N250, and N350, reflecting the application of 50, 150, 250, and 350 kg NO_3^--N ha^{-1}. The experiment was conducted at a level radish field to avoid fertilizer N loss with surface runoff. The tracer was applied 9 days after the broadcast fertilization of the radish field. The process of ridging resulted in the accumulation of the biggest portion of the fertilizer in the ridges. After the ridging, the ridges were covered with impervious black PE mulch and radishes were sown 4 days after the tracer application. Soil and plant samples were taken at day 25, 50, and 75 after sowing and analyzed for ^{15}N using an EA-IRMS coupling. To estimate N loss with percolation, suction lysimeters combined with a soil hydrological monitoring network of standard tensiometers were installed. In each plot, two suction lysimeters were placed in the ridge (15 cm and 45 cm from the top of the ridge), and one was placed in the furrow (45 cm from the top of the ridge) (Figure 13). Suction lysimeters were used to determine the NO_3^- concentrations in seepage water over the time of the growing season, but they provide no information on water fluxes. Quantifying NO_3^- losses with downward percolation can be highly challenging due to these uncertainties associated with estimating the drainage fluxes (van der Laan et al., 2010). Therefore, the process-based numerical model Hydrus 2D (Simunek, 2006) was used for the estimation of NO_3^- leaching losses separately for both the ridge and the furrow zones. The calibration of the model was performed using the measured data of NO_3^- concentrations in seepage water and the tensiometric data to ensure the reliability of the inverse simulation of water flow in soil and solute transport. The only unmeasured sink term for NO_3^- in soil was denitrification, which was simulated as a first order kinetic process.

The results and findings of the ^{15}N recovery in plants were presented in detail in chapter 1.6.1. The results of the ^{15}N retention in soil showed the highest potential for NO_3^- losses during the first 25 days of growth for all N addition rates and in both the ridges and the furrow zones. During these first 25 days of growth, plants in the ridges had not yet emerged and tracer recovery in plants was very low. In contrast, the furrows were uncovered and only little affected by ^{15}N uptake by crops during the entire growing season. Based on the result that ^{15}N retention in soil decreased similarly for ridges and furrows, we conclude that the plastic mulch did not effectively protect the fertilizer in the ridges during this period. The uncovered planting holes with a diameter of 5 cm, in which the water could freely infiltrate into the ridges, might be responsible for that finding. From day 25 to 50 of growth, we observed an increased ^{15}N uptake by plants in the ridges that further reduced the ^{15}N retention in the ridge soil. Several studies additionally suggest that the presence of well-developed crops has much effect on the pattern of water infiltration into the soil and that stemflow from well-developed crops increases the infiltration of water into the ridge soil (Leistra and Boesten, 2008). Stemflow was not experimentally measured in the field in this study, but based on the decreasing ^{15}N retention in soil during day 25 to 50 we conclude that stemflow might be a possible process that diminishes the protective function of the PE mulch during this period. The ^{15}N retention in soil at the end of the experiment was measured to be very low at all fertilizer N rates and showed no statistically significant differences between the different N addition rates. Differences in ^{15}N retention in soils for ridges and furrows were also not statistically significant. Based on these finding, we conclude that the PE mulch had no significant effect on ^{15}N retention in soil during any time of the growing season and did therefore not protect the fertilizer in the ridges from being lost. Based on the low NUE results for all fertilizer N rates shown in chapter 1.6.1, the plastic mulch had also no positive effect on NUE.

The measured NO_3^- concentrations in seepage water were highly consistent with the results of the ^{15}N retention in soil. The total NO_3^- concentrations in seepage were highest during the first 25 days of growth for all N rates, when concurrently ^{15}N retention in soil strongly decreased for all N rates (Figure 12). Based on these results, we conclude that the fertilizer NO_3^- leaching risk in the sandy soils with their low water and nutrient retention capacity was highest at the beginning of the growing season, when the crops had not yet emerged. Based on these results, we also conclude that NO_3^- leaching is the major fertilizer N loss pathway, when plant N uptake is low. However, because the seepage water was only collected weekly, the effect of single rain events on NO_3^- concentration in seepage water could not be captured experimentally. The differences in the NO_3^- concentrations in the furrow and the ridge zones were found to be statistically not significant. Accordingly, the PE mulch, which covered the ridges, did not affect the NO_3^- concentrations in seepage water in the ridges and the furrows and did therefore not protect the fertilizer N in the ridges from percolating into deeper soil layers and to the groundwater. As discussed above, the uncovered planting holes during the first 25 days of growth and the stemflow induced by the well-developed crops from day 25 on are the most probable explanations for these findings. We also observed that the seasonal pattern of the NO_3^- concentrations was not affected by the PE mulch. Increases and decreases of NO_3^- concentrations during the growing season in the ridge and furrow zones were found to be identically. In contrast, the seasonal leaching pattern was clearly influenced by the N addition rate. The continuous and quick decline of NO_3^- concentrations in seepage water at the two lower rates of N50 and N150 resulted in concentrations lower than 10 mg NO_3^- l^{-1} at the end of July (day 45-50 after sowing). The slower and discontinuous decrease of NO_3^- concentrations at N250 and N350 resulted, however, in higher concentrations at the end of July (> 40 mg l^{-1}) and at the final harvest (> 10 mg l^{-1}). These results imply that the major portion of the fertilizer N at the N addition rates N50 and N150 was lost to plant uptake and leaching by day

50. Additionally, the mean seasonal NO_3^- concentrations in seepage water increased with an increase in fertilizer N rate. However, none of the fertilizer N rates did meet the WHO water quality standards of 50 mg NO_3 l^{-1} (WHO, 2011). This is even more remarkable as the NO_3^- concentrations of the seepage water were stronlgy diluted by the massive rainfall.

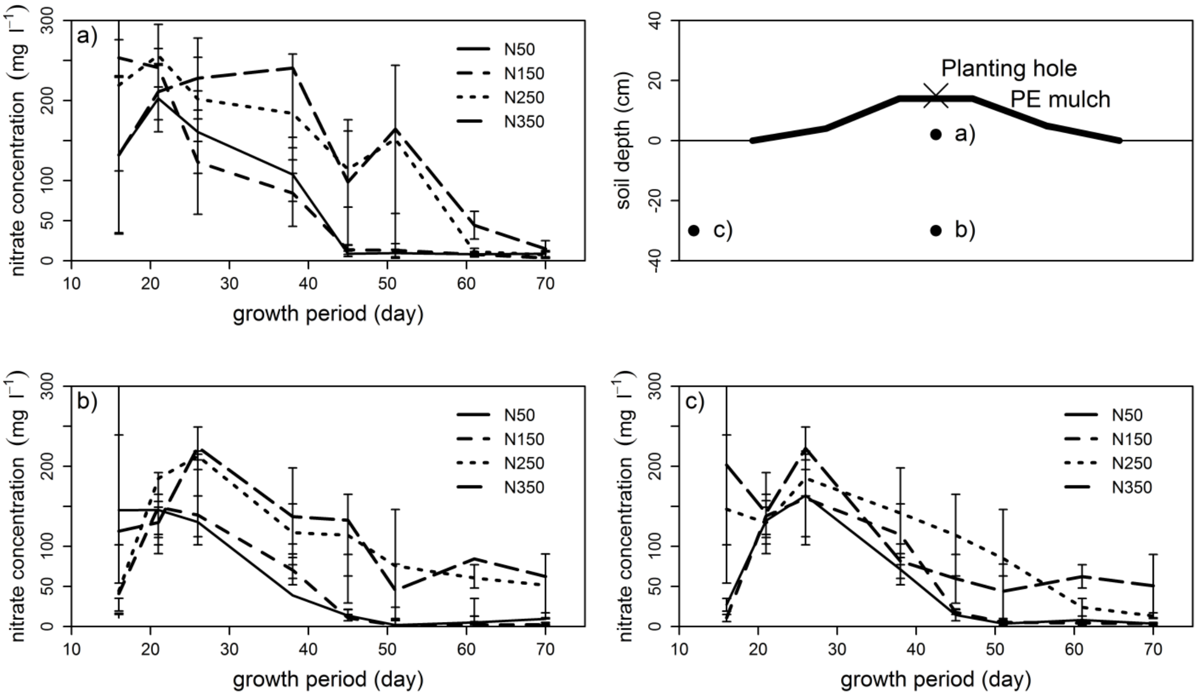

Figure 12 Mean (n=3) NO_3^- concentrations in seepage water (mg l^{-1}) at ridge and furrow positions and two soil depths (15 cm, 45 cm) at the 4 fertilizer N rates. a) = ridge in 15 cm depth; b) = ridge in 45 cm depth; c) = furrow in 45 cm depth. The graphic above right shows the location of the suction lysimeters for collecting seepage water. Broadcast application of the ^{15}N tracer was conducted 4 days before experiment start (=day 0)

For our modeling study of NO_3^- leaching, the amount of precipitation was multiplied by 2 to include the surface runoff from the plastic mulched ridges to the furrows. Accordingly, the furrows contributed the approximately double amount of seepage water to the total amount than the ridges. The simulations showed clearly that the generation of seepage water was strongly affected by rainfall and increased significantly with each heavy rain event. The same findings were observed for the NO_3^- leaching (Figure 13) and the contributions to the total amount of leached NO_3^- peaked during heavy rain events at all N addition rates. The risk of NO_3^- leaching during these rain events was pronounced in both the furrow and the ridge zones. Based on these findings, we conclude that the PE mulch provided little protection for the fertilizer N in the ridges during the heavy rainfall. Subsequently, we found that the ridges and furrows contributed approximately an equal amount of leached N to the total amount at the N addition rates N50, N150, and N250. At the N addition rate N350, however, the furrows contributed considerably more leached NO_3^- to the total amount than the ridges. This higher contribution from the furrows at N350 might be linked to the higher amount of fertilizer N in the furrow soil. This assumption is supported by the finding that, even the contributions from ridges and furrows are fairly similar at N50, N150, and N250, the two lower N addition rates showed slightly higher contributions from the ridges, while at the two higher rates the higher contribution was found in the furrow zones. However, the simulated amount 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. This was also found in leaching studies in R/F cultivation systems without plastic mulched ridges (Errebhi et al. 1998; Shrestha et al. 2010). As this study was conducted in a R/F cultivation with plastic mulch cover, we conclude that the application of PE mulch on the ridges did not prevent a linear or rapid increase of NO_3^- leaching with an increase in fertilizer N addition. While the total amounts of leached NO_3^- increased linearly with an increase in the N addition rate, biomass production did not show the same effect. Accordingly, the negative effect of water pollution at the two higher N addition rates of N250 and N350 was greater than the positive effect of higher biomass production. This indicates high environmental costs caused by exceeding optimum fertilizer N rates.

Based on our findings we summarize that for the reduction of NO_3^- leaching losses, the reduction of fertilizer N addition rates is the major scope of action. The PE mulch did not protect the fertilizer N in the ridges from leaching nor did it prevent the linear increase in total NO_3^- leaching losses with an increase in fertilizer N rate. The plastic mulch in Haean Catchment is used to allow an early planting in the spring and thus to extend the growing season. Without the application or use of other measures or methods, the application of PE mulch in a summer monsoon climate with heavy rainfall events does not positively influence the NO_3^- leaching rates. Possible treatments found in the literature might be the precision placement of nutrients, split applications of fertilizer, and covering the furrows with plant residues. The application of PE mulch, however, makes in turn a split application of fertilizer more time-consuming and costly. To develop further methods to reduce NO_3^- leaching under R/F cultivation with plastic mulch, more knowledge about the effect of PE mulch on water fluxes in the soil and at the soil surface is needed.

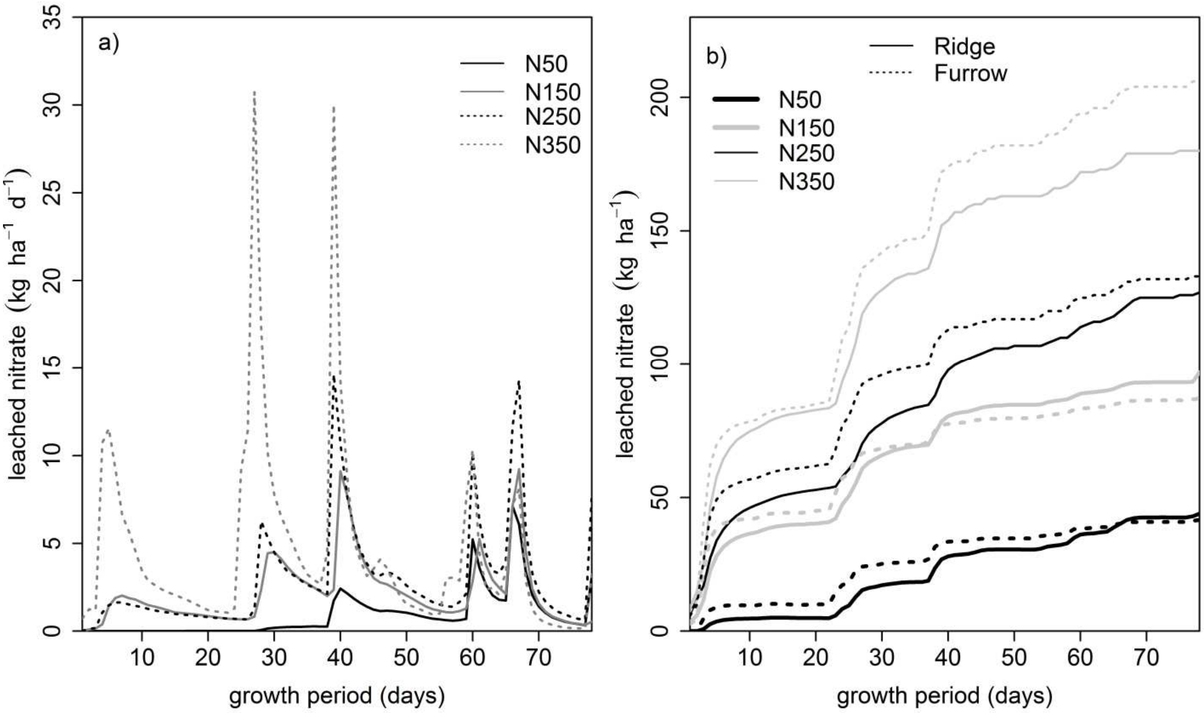

Figure 13 a) Simulated daily leached NO_3^- (kg N ha^{-1} d^{-1}) for the 4 fertilizer N rates and b) simulated cumulative leached NO_3^- (kg N ha^{-1}) for ridges and furrows separately during the growth period of 75 days

1.6.4 Water flow influenced by R/F cultivation with PE mulch (Chapter 4)

To investigate the influence of the plastic mulched ridges on the soil water dynamics and the water fluxes, we set up a monitoring network of tensiometers and FDR sensors in two sloped potato fields in Haean Catchment. The monitoring devices were installed in 15, 30, and 60 cm soil depth in the furrows and in the plastic mulched ridges, respectively. Further, the monitoring network was installed at the upper, the middle, and the lower slope of the field. The obtained data set was then used to calibrate the numerical model Hydrus 2D using the inverse modeling technique. To understand in detail the influence of the plastic mulched ridges on the soil water dynamics and the water movement, we simulated the different cultivation scenarios: 1) conventional flat tillage (CT); 2) R/F cultivation without plastic mulched ridges (RT); and 3) R/F cultivation with plastic mulched ridges (RTpm).

The observed and simulated soil water pressure, which is generally expressed as pressure head h (cm), showed generally a good agreement, but the agreement of the pressure heads for field site 2 was less sufficient than for field site 1 (Figure 15). We found that the wetting events were simulated reasonably well at both field sites, while the dry periods were underestimated at both field sites but especially at field site 2. The simulation results for a small rain event (8-11 mm) after a period of 7 dry days showed considerable differences in soil water dynamics for the plastic covered ridges and for the bare furrows in the RTpm cultivation. The pressure heads in the ridge positions were found to be lower than in the furrow positions, indicating less infiltration in the ridges and/or a high water uptake by plants in the ridges after the plants had emerged and further developed. The pressure head gradients were observed to be distinct horizontally, which in turn led to a lateral soil water flow from the wetter furrows to the drier ridges. These differences between ridges and furrows were observed to be weakened under the RT cultivation. The soil moisture in the RT cultivation without PE mulch was only affected by the microtopography, namely the ridges and the furrows, but not by the PE mulch. For the CT cultivation, lateral flow was not observed at all because the pressure head gradients were found to be exactly vertical, resulting in a water flow directed from the top layer to the sublayer of the soil. Based on these findings we conclude that during dry periods both the ridge and furrow configuration and the PE mulch affect and alter soil water dynamics. It was also demonstrated that the PE mulch amplifies the alteration of the soil water dynamics induced by the R/F cultivation. Additionally, we observed that the soil texture also influences the pressure heads. At field site 1, which is characterized by a soil texture change between the A- and the B-horizon, the differences in pressure heads were only found in the A-horizon. However, at field site 2 with two fine-textured horizons the differences in pressure heads were distinct even in the B-horizon.

The simulation results for the soil water dynamics during a monsoon event (50-51 mm) showed less clear findings for the effects of the PE mulch on soil moisture. Field site 1 and 2 showed different results during the monsoon event and the dominating flow directions were therefore less pronounced than for the dry period. At field site 1 under the RTpm cultivation, no effect of plastic mulched ridges on soil water dynamics was observed at all. The pressure heads from the ridge and the furrow positions were similar due to the high hydraulic conductivity of the soil in the A-horizon, which in turn led to a quick and homogeneous distribution of the water in the soil. As a result, the pressure head gradients were distinct vertical, resulting in a water flow directed from the top layer to the sublayer of the soil. At field site 2 under RTpm cultivation, however, the effect of the PE mulch on the pressure heads during a monsoon event was more evident. The lower hydraulic conductivity of the soil in the top layer resulted in a slower water distribution and a part of the soil below the PE mulch remained unsaturated. These results were observed in the top layer as well as in the sublayer of the ridges. Based on these findings we conclude that the soil texture and the hydraulic conductivity are important factors, which determine whether the PE mulch affects the soil water dynamics during heavy rainfall events or not. For RT cultivation without PE mulch the hydraulic conductivity of the soil plays a less important role because the water infiltration was found to be more homogeneous than under the RTpm cultivation. Therefore a fully saturated B-horizon with distinct horizontal isolines was observed.

The simulation results for the cumulative water fluxes varied strongly between both field sites due to different dominating flow directions as a result of different bottom boundary conditions. The subjacent granite bedrock material forced water to move laterally in slope direction at field site 1, while water percolated at the bottom boundary at field site 2, which induced a vertical water movement. To investigate the effect of the PE mulch on water fluxes, we simulated the cumulative water fluxes at the transitions from furrows to ridges as well as at the transition from ridges to furrows. At field site 1, the PE mulch led to a reduction of water fluxes under the RTpm cultivation compared to the water fluxes at RT and CT cultivation, but the differences in the total amount of seepage water fluxes were negligible between the RT cultivation system with and without PE mulch due to an increased evaporation rate without the PE mulch (Figure 14). At field site 2, however, the vertical water movement resulted in positive water fluxes at the transition from furrows to ridges and in negative water fluxes at the transition from ridges to furrows in slope direction as a result of lower pressure heads below the PE mulch. This effect was observed to diminish under RT cultivation without plastic mulch. Under CT cultivation, the exclusively negative values represent the high influence of free drainage conditions at the bottom. To summarize the effect of the plastic mulch on water fluxes, the drainage water at field site 1 was comparable between all management strategies, whereas the drainage water at field site 2 was about 16% higher without PE mulch than with PE mulch. The evaporation rate was 40% higher without PE mulch at field site 1 and 48% at field site 2, respectively, than with PE mulch. Surface runoff increased under RTpm about 65% compared to the RT cultivation without plastic mulch. The transpiration, however, was not influenced by the plastic mulch cover. The RTpm cultivation was therefore found to have the lowest amount of drainage water, the lowest evaporation rates but also the highest runoff rates, while the RT cultivation without PE mulch showed the lowest runoff rates of all management practices. Based on these finding, we conclude that the plastic mulching might be assessed as a tool to reduce percolating water with the additional effect of earlier planting in spring and suppressing weed, but it was also shown that the PE mulch concurrently increases water contribution to the river network by surface runoff.

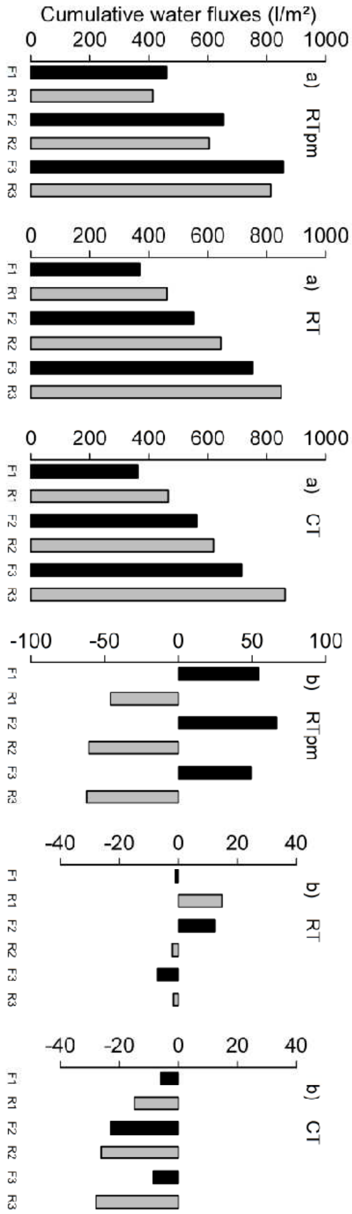

Figure 14 Cumulative water fluxes at the transition from the furrows to the ridges and from the ridges to the furrows in slope direction. Due to different bottom boundary conditions at both field sites, only positive cumulative water fluxes were simulated at field site 1 (a), which was characterized by mainly lateral water movement. At field site 2 (b), the vertical water movement resulted in positive and negative water fluxes. R = Ridge, F = Furrow. RTpm = R/F cultivation with PE mulch, RT = R/F cultivation without PE mulch, CT = conventional flat cultivation. F1-3 reflect water fluxes, which come from the furrows but contribute to the ridges in slope direction, R1-3 represent water fluxes, which come from the ridges but contribute to the furrows in slope direction

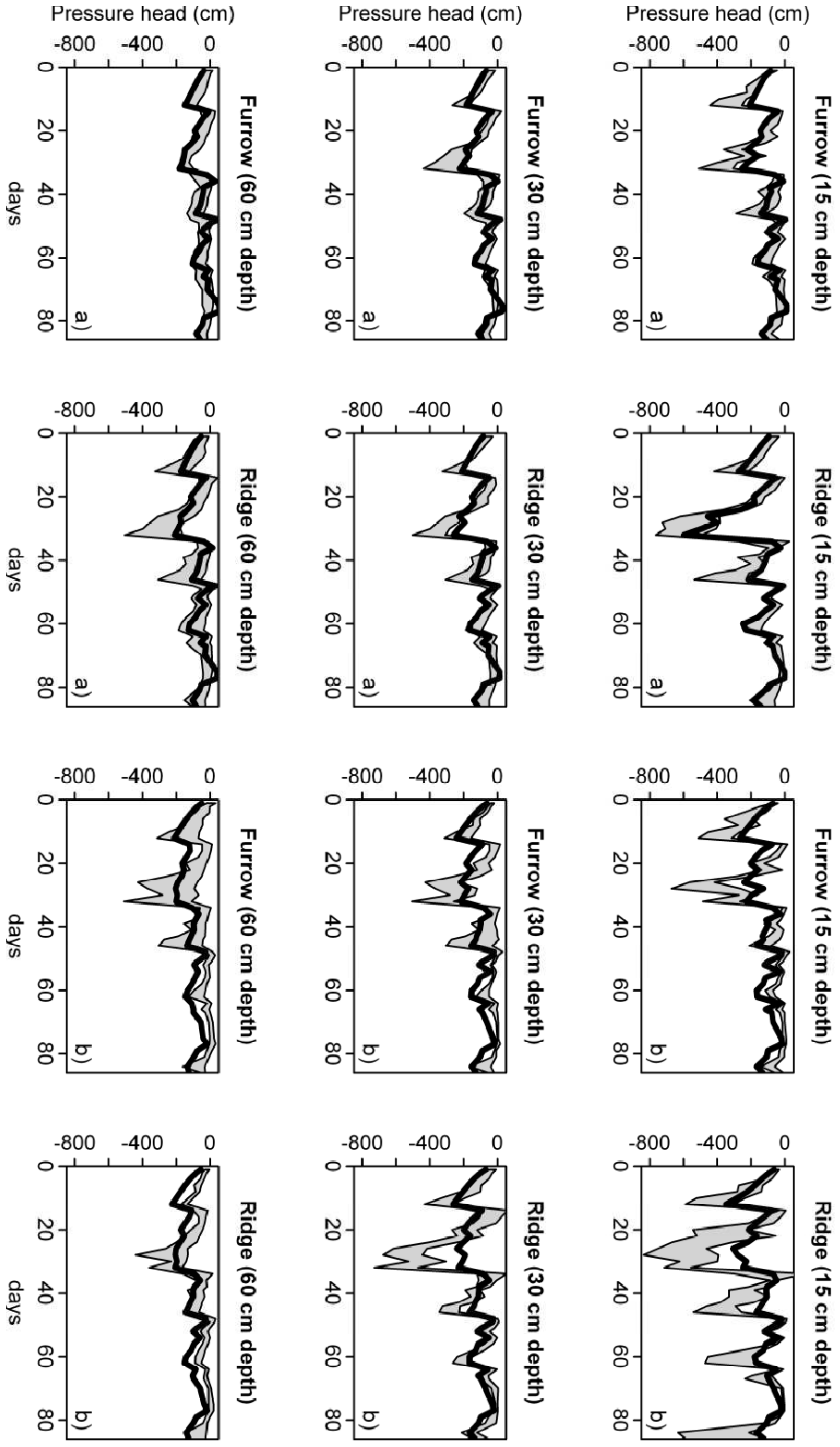

Figure 15 Observed vs. simulated pressure heads in different depth for a) Field site 1 and b) Field site 2; limits of grey area = +/- standard deviation of the observed data, black solid line = simulated pressure heads

1.6.5 Concluding remarks and recommendations for further studies

This thesis began with the idea to summarize the major N fluxes of the N cycle in the Haean Catchment in collaboration with other projects within the framework of TERRECO.

In the first approach, we used N flux values and N flux estimates to construct N field budgets and to compare the extrapolated catchment N budget to measured N leaching to water bodies in the catchment. We successfully determined the most important N parameters, except N mineralization from SOM. A major problem was to determine the exact N fertilizer rates applied by the local farmers. We therefore used statistics for Gangwon Province. To check and revise the statistics and their reliability for the Haean Catchment, we aimed to measure N_{min} values before the application of fertilizer in spring, a few days after fertilizer application, and at the end of the harvest. This intention, however, was complicated by several factors such as lack of information and fertilizer application method. N_{min} values are therefore an uncertainty within the budget calculations. Haean Catchment is an advantageous location for the calculation of N budgets at landscape scale because it allows comparisons with the N export calculated for the basin. To provide an accurate extrapolation, measured field budgets for perennial crops should be included in further calculations. To include perennial crops into the calculation, long-term N budget calculations are required. The incorporation of perennial crops is also an essential next step because the cultivation of perennial crops is increasing and highly promoted by local governments as well as promoted by the regional warming. Finally, the NUE is calculated as harvested amount of N over the amount of applied fertilizer N. In further studies, it would be interesting to make these calculations based on unfertilized plots, so that the NUE was calculated as the fertilizer induced N biomass increase over the amount of applied fertilizer N. This would give a clearer insight on which tools should be applied to reduce N losses.

In a second approach, we measured ^{15}N fate in a R/F cultivation and simulated NO_3^- leaching amounts. We successfully investigated: (1) the biomass production of radish; (2) the radish N uptake; (3) and the N retention in soil using ^{15}N fertilizer in a radish cultivation. It was not possible to determine ^{15}N content in the seepage water. We therefore measured NO_3^- concentration in the seepage water and simulated drainage fluxes as well as NO_3^- leaching amounts with a soil hydrology model. NO_3^- concentration in seepage water was collected and analyzed weekly. However, to investigate the effects of heavy rain events on NO_3^- leaching, the seepage water should not be collected in certain intervals in further studies but right after the heavy rainfall events. To diminish the influence of the underpressure on NO_3^- concentration in seepage water, the different sampling depths and locations of suction lysimeters should be connected to several vacuum pumps. An interesting finding of this study was the fact that NO_3^- concentrations in seepage and ^{15}N retention in soil was not statistically different for ridges and furrows. Further studies need to investigate and measure the processes within ridges and furrows more detailed and have a more detailed look at the water fluxes, which are an important factor for the N fate. In further studies, it would be interesting to measure and compare the N fate of different management systems such as R/F cultivation with PE mulch, R/F cultivation without PE mulch, and conventional flat cultivation. Additionally, the measurement of the influence of split fertilizer applications and fertilizer placement on NO_3^- leaching and NUE would give a clearer insight on N saving potentials. Another interesting future aspect is to investigate the NO_3^- leaching amount at sloped field sites as Haean Catchment is a mountainous agricultural catchment. Regarding the simulations, it will be interesting to compare the simulated N leaching amounts of Hydrus 2D with the simulated NO_3^- leaching amounts of DNDC, which is used by another project to determine N emissions and NO_3^- leaching.

A third approach was to simulate how and to which extend the water flow regime in sloped fields is modified by R/F cultivation. As the Hydrus 2/3D code does not calculate surface runoff directly, it was necessary to multiply the precipitation data with a factor of 2 for indirectly simulating runoff from the ridges to the furrows. This simplified method does not reflect the real field conditions, although the simulation results between observed and simulated pressure heads showed that the multiplication method was adequate to overcome the problem in calculating surface runoff. However, further studies should quantify surface runoff from ridges to furrows for different growing stages during the growing season. Additionally, the simulation neglected that interception on the crop canopy plays a relevant role for water infiltration, especially during the main growing stage. Field observation showed that the potato canopy covered up to 80% of the surface area and therefore had a great influence on water redistribution. Further simulation studies should therefore simulate canopy architecture and related flow processes like stemflow. Stemflow should additionally be measured for different growing stages during the growing period and for different rainfall intensities. Finally, root development during growing season could not be simulated and might result in an overestimated root water uptake at the beginning of the growing season, which in turn affects parameter optimization. The multitude of factors influencing infiltration as well as water and solute fluxes is a huge challenge for measuring, analyzing and modeling these mechanisms and further studies should concentrate on measuring and incorporating more of these challenges into the simulations.

1.7 List of manuscripts and specification of authors' contribution

This thesis includes 4 manuscripts. Two are submitted and reconsidered for publication after major revision, one is submitted and in review, and the fourth one is in preparation. The list below details the contributions of all co-authors.

Manuscript 1

Authors	Kettering, Janine; Park, Ji-Hyung; Lindner, Steve; Lee, Bora; Tenhunen, John; Kuzyakov, Yakov	
Title	N fluxes in an agricultural catchment under monsoon climate: An extensive budget approach at landscape scale	
Status	published	
Journal	Agriculture, Ecosystems and Environment, Vol. 161, p. 101-111	
Contributions	Kettering	idea, methods, data collection, data analysis, figures, manuscript writing, manuscript editing, corresponding author
	Park	data collection, data analysis, editing
	Lindner	data collection
	Lee	data collection
	Tenhunen	editing
	Kuzyakov	idea, discussion, editing

Manuscript 2

Authors	Kettering, Janine; Ruidisch, Marianne; Gaviria, Camila; Ok, Yong-Sik; Kuzyakov, Yakov	
Title	Fate of fertilizer ^{15}N in intensive ridge cultivation with plastic mulching under a monsoon climate	
Status	in revision	
Journal	Nutrient Cycling in Agroecosystems	
Contributions	Kettering	idea, methods, data collection, data analysis, figures, manuscript writing, manuscript editing,

		corresponding author
	Ruidisch	data collection, data analysis, modeling
	Gaviria	modeling
	Ok	editing
	Kuzyakov	idea, discussion, editing

Manuscript 3

Authors	Ruidisch, Marianne; Kettering, Janine; Arnhold, Sebastian; Huwe, Bernd	
Title	Modeling water flow in a plastic mulched ridge cultivation system on hillslopes affected by South Korean summer monsoon	
Status	in press	
Journal	Agricultural Water Management	
Contributions	Ruidisch	idea, methods, data collection, data analysis, figures, manuscript writing, manuscript editing, corresponding author
	Kettering	data collection, data analysis, manuscript editing
	Arnhold	data collection
	Huwe	idea, discussion, editing

Manuscript 4

Authors	Kettering, Janine; Kuzyakov, Yakov	
Title	Ridge and furrow cultivation: challenges for analysis of water fluxes and nutrient leaching	
Status	in preparation	
Journal	-	
Contributions	Kettering	idea, data collection, data analysis, figures, manuscript writing, manuscript editing, corresponding author
	Kuzyakov	manuscript writing, discussion, editing

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Chapter 2 N fluxes in an agricultural catchment under monsoon climate: An extensive 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.

Keywords: N surplus / N export / N use efficiency / catchment scale / rice paddy / dryland crops

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 SOM (soil organic matter) 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 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} yr^{-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 a 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 not only an advantageous location 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' to 128°11’ E, 38°13' to 38°20’ N) in Yanggu County, Ga ngwon Province, South Korea. Elevation ranges between 339 to 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℃ 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 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).

Table 1 Selected initial soil characteristics of the top layer (0-30 cm) at the experimental sites. I. shows the soil characteristics of the dryland field sites and II. shows 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.

I. Dryland field sites

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}** *$kg\ ha^{-1}$*
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)*	0.06 *(±0.05)*	6.04 *(±0.63)*	NO_3^-: 93 *(±19)* NH_4^+: 98 *(±11)*

II. Rice paddies

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}** *$kg\ ha^{-1}$*
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)*	0.08 *(±0.06)*	8.72 *(±0.70)*	NO_3^-: 9.96 *(±9.96)* NH_4^+: 59 *(±6.49)*

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; Lamont, 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.

Table 2 Land use in the Haean Catchment in 2009. I. total catchment area. 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**

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.

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 cm)	Fertilization times(+timing)	Fertilizer rates kg N ha^{-1}	Plastic Mulching
Soybean	**End May-End Oct.**	**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 Aug.**	**90-120**	**1-2 (20-30)**	**1 (basal)**	**Basal:137**	**Yes, black PE**
Radish	**Beg. June-End Aug.**	**70-80**	**1 (15-20)**	**1-3 (basal+ additional)**	**Basal:88 Add.:164**	**Yes, black PE**
Rice	**Mid May-Mid Oct.**	**160-180**	**2 (15-30)**	**1-2 (basal+ additional)**	**Basal.50 Add.:20+20**	**No**

Crop	Irrigation	Plant density in cm / Row density in 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**

Soil samples were taken (five cores from each field) from 0-30 cm three times: before fertilizer application, shortly after fertilizer application and at harvest time. The five field replicates were mixed, weighed, and extracted with 1M 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℃ 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℃ 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-yr 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. Grab samples of water were collected in midstream approximately 10 cm below the stream surface using PTFE bottles and were kept refrigerated at < $4^{o}C$. Within 24h, 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 equation 1 (Clark et al., 2007).

$$F = K * Q_r (\Sigma C_i Q_i / \Sigma Q_i) \quad (1)$$

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 were taken as average values from the years 2007 to 2009 out of statistical yearbooks for Gangwon Province (RDA, 2008; RDA, 2009; RDA, 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 0-30 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} yr^{-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 one hectare. 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 were 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 analysis. 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 (Figure 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}.

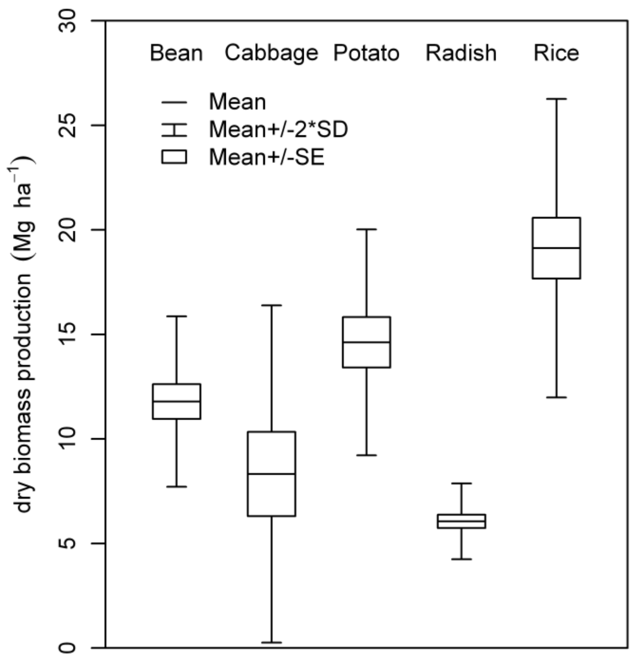

Figure 1 Measured biomass (dry) of the 5 key crops in 2009.

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 (Figure 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 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.

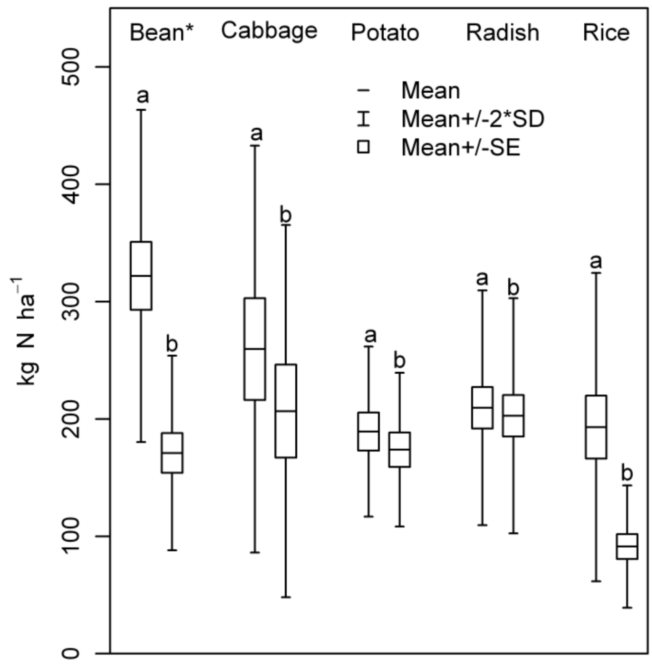

Figure 2 Crop N uptake (i.) at harvest and crop N removal (ii.) with harvest of the five crops in 2009. * marks a significant difference between i and ii. Crop N uptake at harvest illustrates the crop N of all crops at the field site. Crop N removal illustrates only the crop N, which is removed from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

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*

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 x̄/SE/Range	**Cabbage** x̄/SE/Range	**Potato** x̄/SE/Range	**Radish** x̄/SE/Range	**Rice** x̄/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.

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 were 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 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 Figure 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 fixtion, which also led to high total N inputs. Cabbage, radish, potato and rice showed a mean gross N surplus in the range of 190 to 270 kg N ha^{-1} yr^{-1} due to the high N fertilization rates (Figure 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 Figure 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.

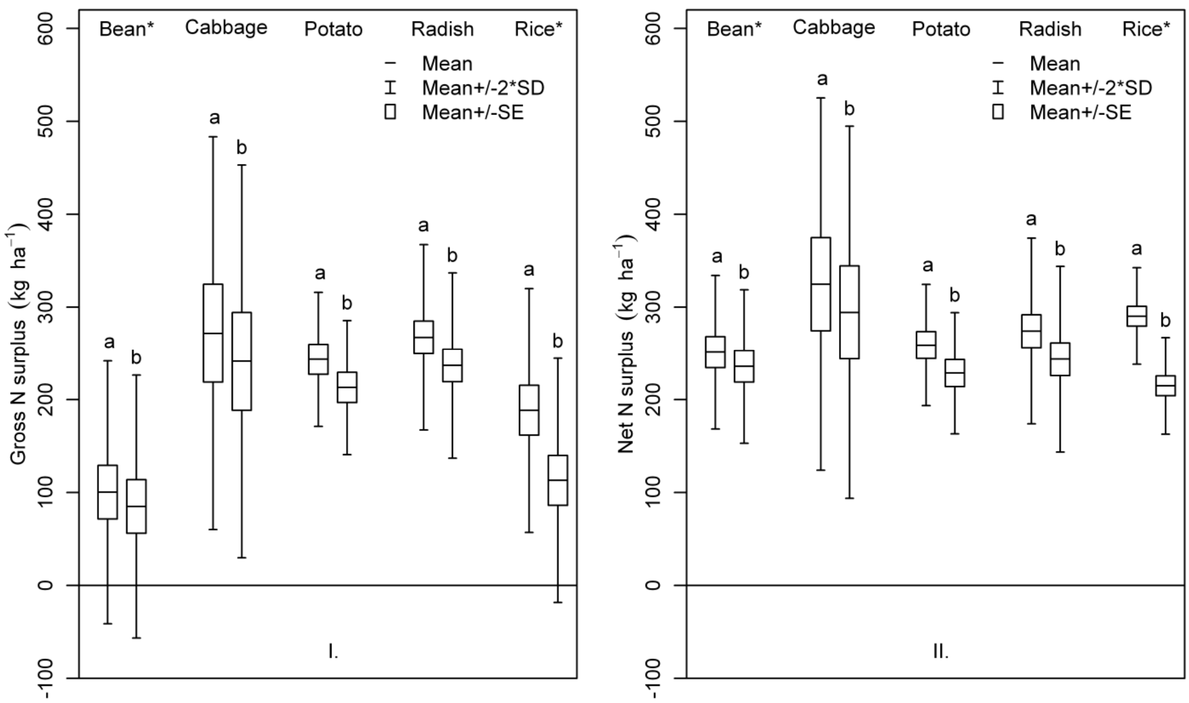

Figure 3 I. Gross N surplus (N input minus total crop N) and II. Net N surplus (N input minus harvest N) calculated with two different approaches. Potential deficits at soybean fields result from the high N uptake by plants and a low fertilizer N input. i = total input-approach; ii = selected input-approach.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

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 agro-ecosystems. 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% (Figure 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.

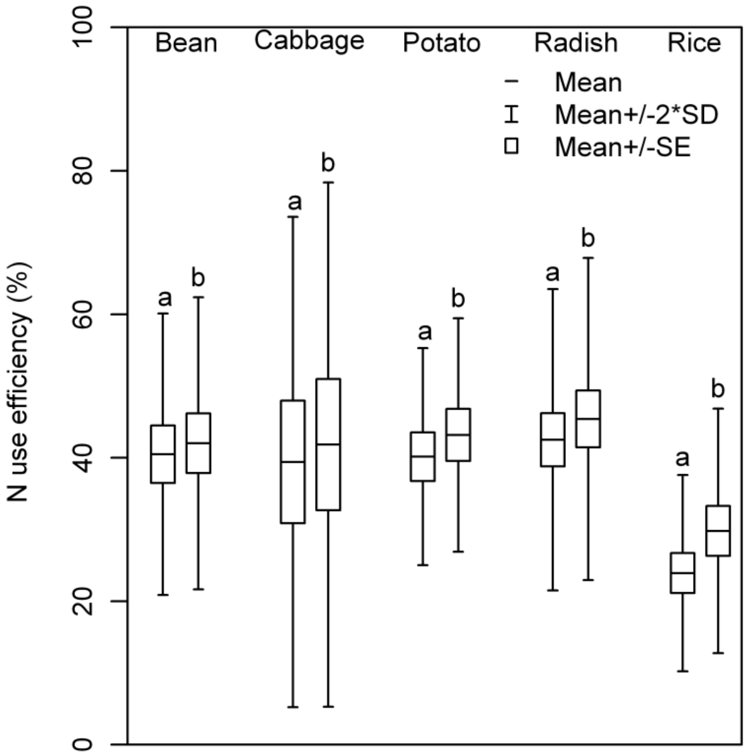

Figure 4 N uptake efficiencies of the five key crops. i: calculated with results of the total input-approach; ii: calculated with results of the selected input-approach.

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 (Figure 5).

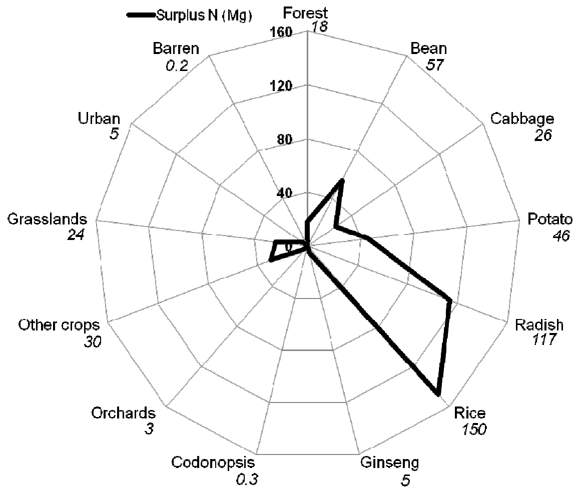

Figure 5 Maximum net N surplus (Mg) for agricultural land and other land use categories at the catchment scale in 2009. Net N surplus was calculated with the total input-approach. Values in *italics* give the amount of total net N surplus of each land use category.

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} yr^{-1} (Shim and Kim, 2005), which averaged to 18 Mg yr^{-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 to 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} yr^{-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} yr^{-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 sec^{-1}. The highest discharges were observed during the summer monsoon season with discharges higher than 100000 l sec^{-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 sec^{-1} at April 24 and October 9 (Figure 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 sec^{-1} and 4.5 g sec^{-1}, respectively, at July 15 and August 13. Lowest export of nitrate and ammonium with the stream water was observed at the beginning and at the end of the growing period with an export lower than 11 g sec^{-1} and 0.6 g sec^{-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.

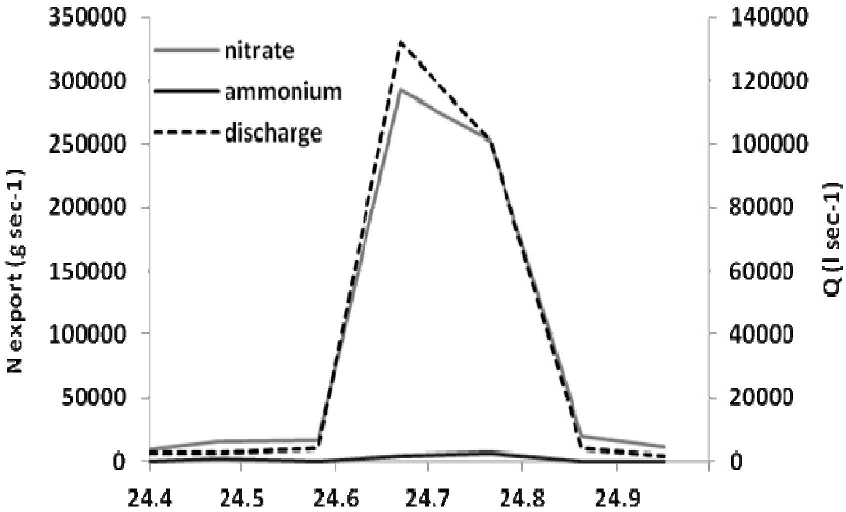

Figure 6 Stream water data of the Mandae stream. Shown are the discharge Q (l s^{-1}) and the nitrate as well as the ammonium export (g s^{-1}) with the only outlet of the Haean catchment during the growing season 2009.

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 (> 70mm) (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 were 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 analysis.

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} yr^{-2} (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} yr^{-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 other 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} yr^{-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} yr^{-1} (Dise and Wright, 1995). Atmospheric N deposition in Haean catchment was measured to be around 15 kg N ha^{-1} yr^{-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; Yanggu

County Office, 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' 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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Chapter 3 Fate of fertilizer ^{15}N in intensive ridge cultivation with plastic mulching under a monsoon climate

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Abstract

Reducting 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) NO_3^- 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 NO_3^--N kg ha^{-1}). The application of plastic mulch in combination with local fertilizer management did not help to reduce NO_3^- 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 NO_3^--N ha^{-1}; 2) applying fertilizer N in 3 to 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

1 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 the soil structure that might induce preferential flow, which is characterized as an uneven and often rapid flow of water and solutes through soil via preferred pathways that results in the fact that only a small part of the soil contributes to most of the flow.

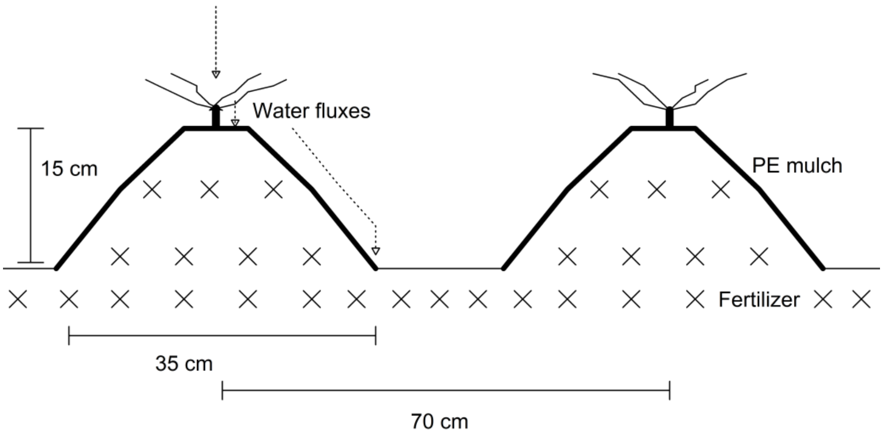

Figure 1 Scheme of a typical ridge cultivation system with plastic mulching used for radish production in a temperate South Korean area with summer monsoonal climate. The water fluxes ( ) and the distribution of fertilizer N (X) in the system are indicated.

Polyethylene (PE) mulch has been used to cover soil surfaces in South Korea for ridge cultivation of vegetable crops (Figure 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 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 NO_3^--N ha^{-1} on top of the basal fertilization rate of 56 kg NO_3^--N ha^{-1}. Because NO_3^- leaching was absent during the dry and cold winter, we conducted the field and the modeling study only during the growing season.

2 Materials and Methods

2.1 Study site

The field experiment was conducted on a typical Korean terric cambisol also considered a 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.

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

Soil depth	**Sand**	**Silt**	**Clay**	**Texture**$^{\Psi}$	$\mathbf{d_B}$
cm	*%*	*%*	*%*		*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)*

$^{\Psi}$ Soil texture taken from the World Reference Base of the IUSS Working Group (2007)
The standard error of the mean is given in italics in the parentheses

Daily precipitation and temperature data were monitored with an automatic weather station (WS-GP1, Delta-T Devices, Cambridge, UK) at the site (Figure 2) and were compared with meteorological data for the Haean Catchment (own data). 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 annu al precipitation of approximately 1577 mm, with 70% of the precipitation occurring 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 mm 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 mm and 415 mm, respectively. The heaviest rainfall during the experiment was 150 mm in the three days from August 13 to 16 (Figure 2a). Although no runoff was observed throughout the experimental period, water sometimes ponded on the furrow surface after a heavy rainfall. For March, April and May, the temperature was colder than the 11-year mean (Figure 2b). This led to a delay in the start of cropping by approximately two to four weeks.

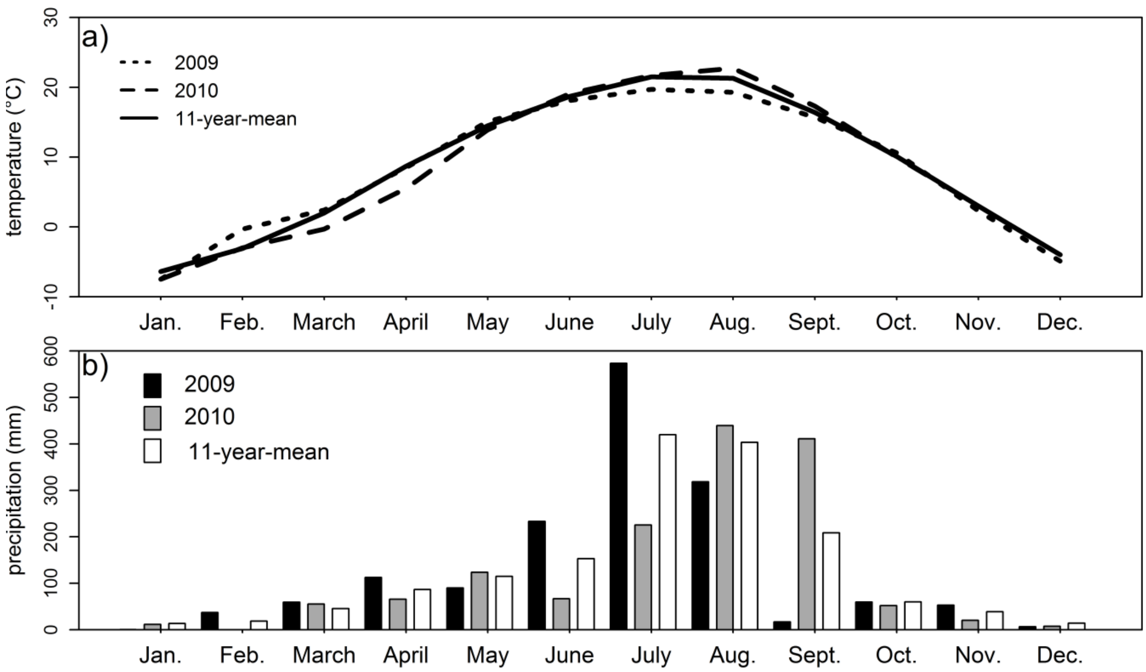

Figure 2 a). Mean daily temperature (℃) and b) mean total precipitation (mm) for the years 2009 and 2010 as well as the 11-year mean (1999-2009) for the Haean Catchment.

2.2 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) 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 (7x7 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 width and 10-15 cm height) was implemented with a distance of 70 cm between the rows. The ^{15}N labeling experiment was performed in microplots (125x75 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 sowed 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.

2.3 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 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 cm 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 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), coefficient of determination (R^2) 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.

Table 2 Comparison of the model evaluation coefficients r, R^2, 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

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.

Table 3 Comparison of the model evaluation coefficients r, R^2, 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

2.4 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℃ 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℃, 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 cm, 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℃ 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).

2.5 ^{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 (at%). ^{15}N concentrations were then converted to an area basis (mg ^{15}N m^{-2}) using equations 3, 4 and 5 (Buchmann et al. 1995):

$$[^{15}N] = {}^{15}N/{}^{14}N \text{ at\%} / 100 * [N] \quad (3)$$

With [N] = N concentration.

$$\text{Plant samples: } {}^{15}N \text{ g m}^{-2} = [^{15}N] * \text{bio g m}^{-2} \quad (4)$$

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

$$\text{Soil samples: } {}^{15}N \text{ g m}^{-2} = [^{15}N] * d_B * s \quad (5)$$

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.

2.6 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. Different statistical techniques such as Pearson's correlation coefficient, coefficient of determination and Nash-Sutcliffe efficiency were used to evaluate the models.

3 Results

3.1 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 (Figure 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 (Figure 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% (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 (Figure 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.

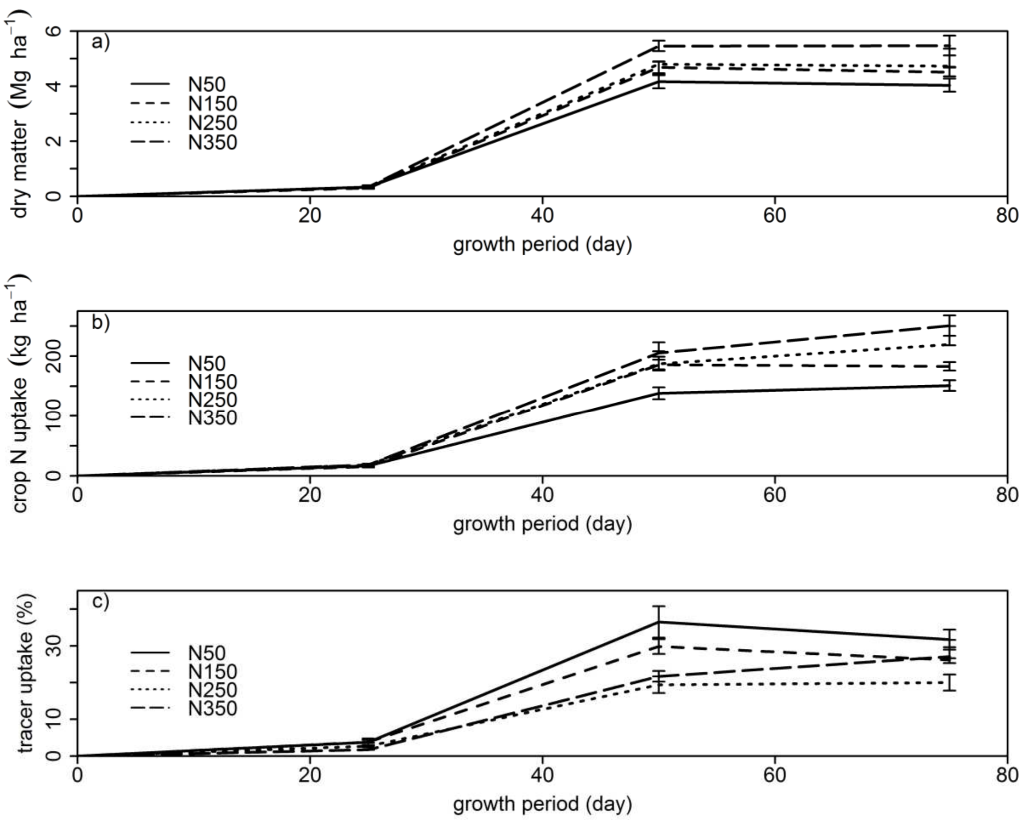

Figure 3 a) Mean dry matter production (Mg ha^{-1}), b) ^{15}N uptake by plants (% of ^{15}N applied), and c) total crop N uptake (kg N ha^{-1}) of radish plants grown at the four fertilizer N rates over 75 days of growth. Error bars are standard error of the mean.

3.2 ^{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 (Figure 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).

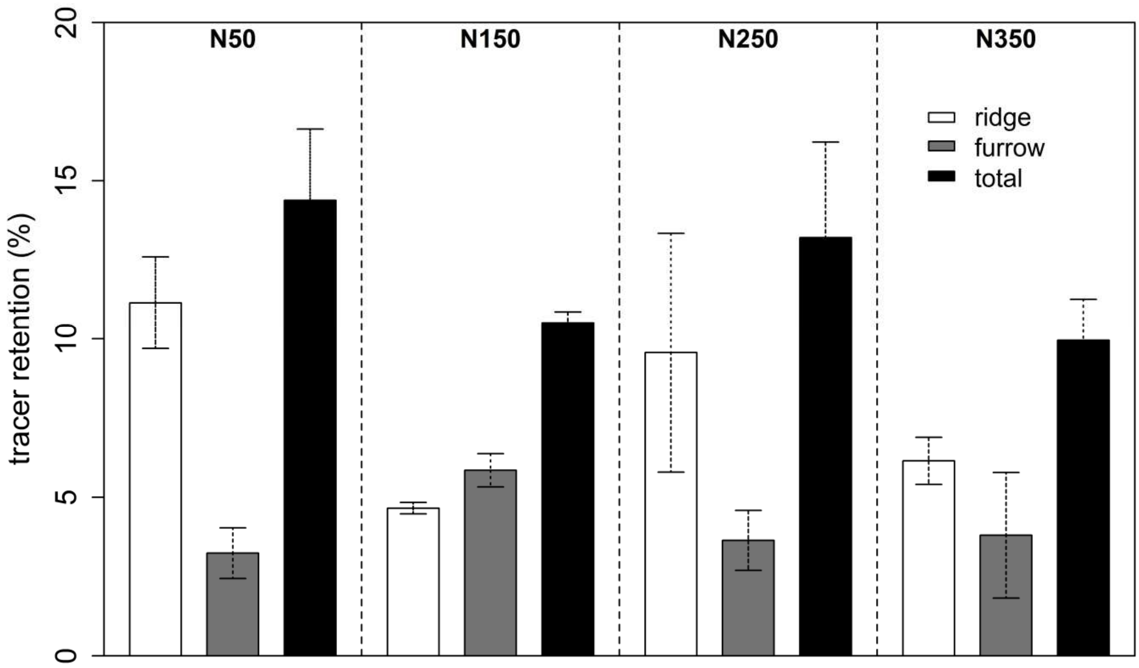

Figure 4 Mean soil ^{15}N retention (% of ^{15}N applied) averaged for all depths at day 75 of growth. Results are given for ridges and furrows separately and totaled for each of the four fertilizer N rates. Error bars are standard error of the mean.

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**	
	0-20cm	*20-40cm*	*40-60cm*	*15-40cm*	*40-60cm*
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)*

3.3 NO_3^- content in soil solution and NO_3^- 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 (N50); 853 (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 (Figure 5). Simulated seepage water fluxes were strongly affected by rainfall and increased considerably with each heavy rainfall event at all N application 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.

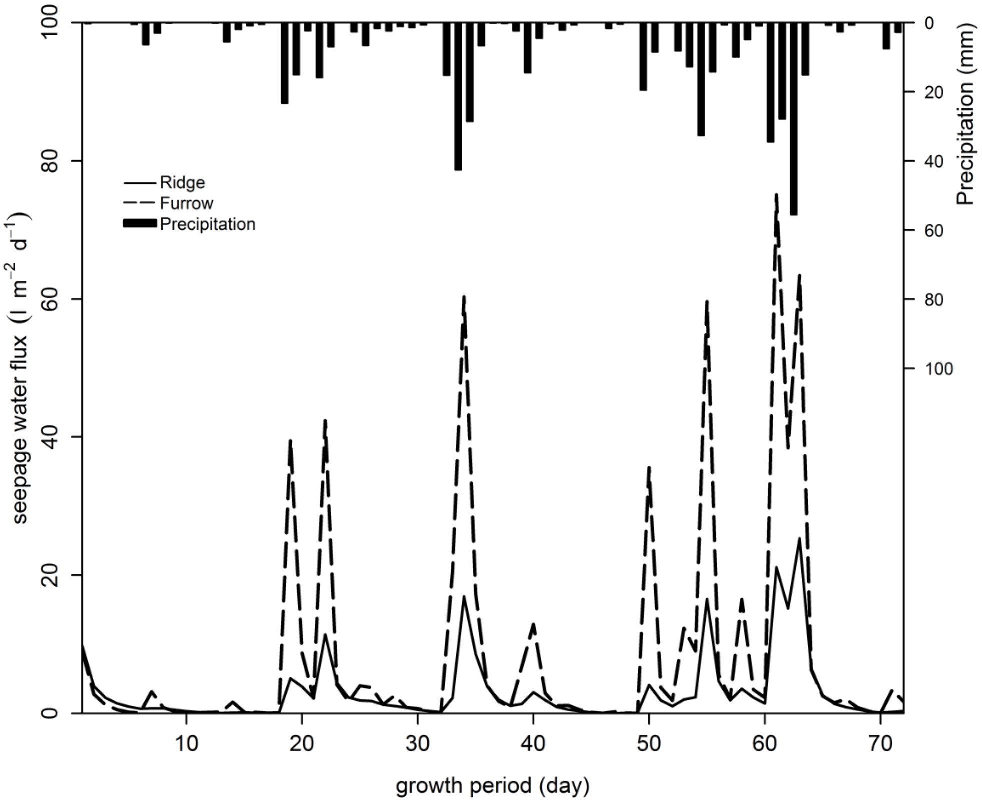

Figure 5 Mean simulated daily seepage water fluxes (l m^{-2} d^{-1}) in soil at a depth of 45 cm during the 75 day growth of a radish crop. Daily seepage water was simulated for one replicate plot of each of four fertilizer N application rate treatments.

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 cm 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 (Figure 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 four 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.

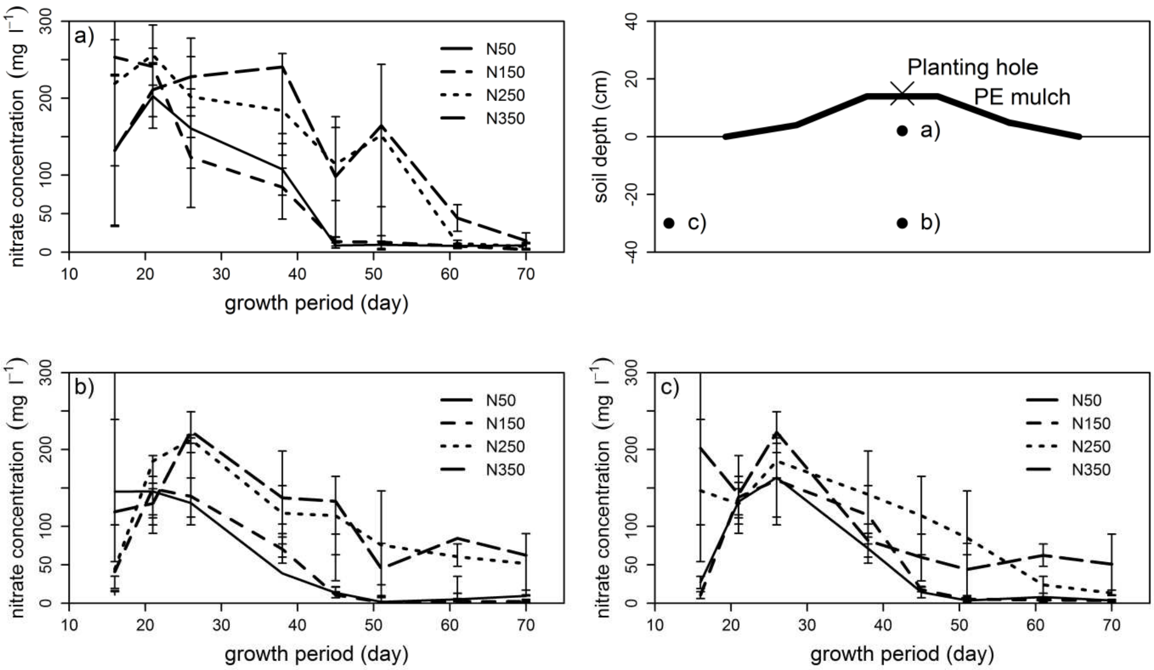

Figure 6 Mean (n=3) nitrate concentrations in seepage water (mg l^{-1}) at ridge and furrow positions and two soil depths (15 cm, 45 cm) for the four fertilizer N rates. a) = ridge at a 15 cm depth; b) = ridge at a 45 cm depth; c) = furrow at a 45 cm depth. The graphic top right shows the location of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

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 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^--N ha^{-1} (N50) < 180 kg NO_3^--N ha-[1] (N150) < 260 kg NO_3^--N ha^{-1} (N250) < 387 kg NO_3^--N ha^{-1} (N350) (Figure 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.

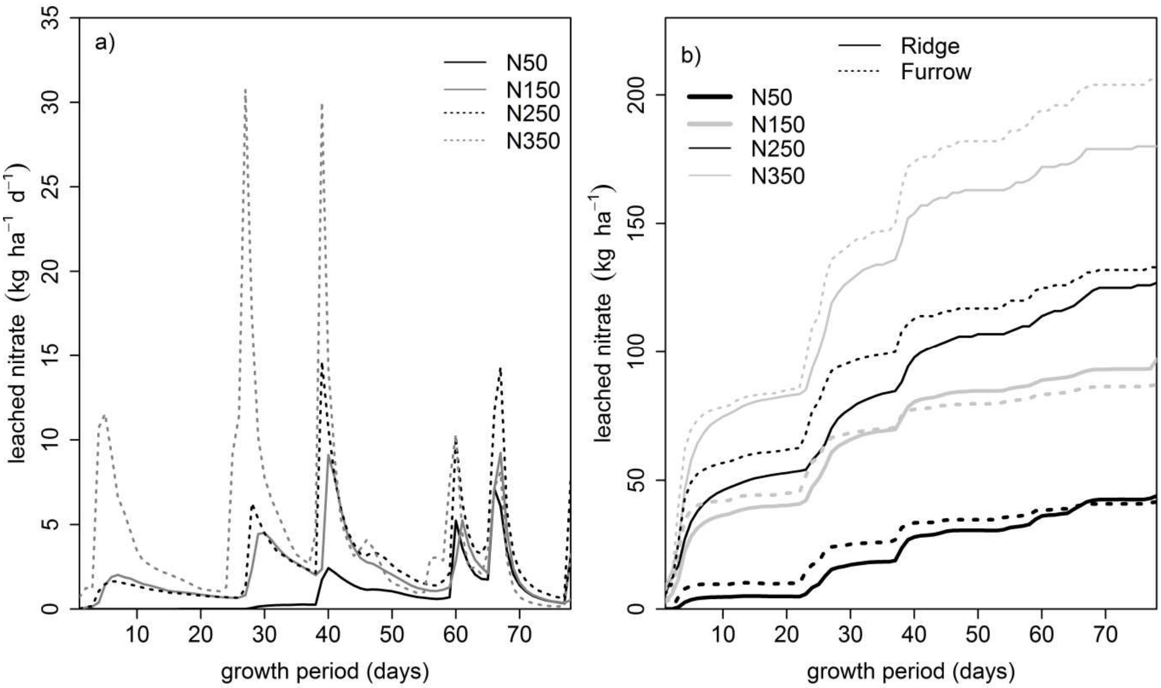

Figure 7 a) Simulated daily leached NO_3^- (kg NO_3^--N ha^{-1} d^{-1}) for the four fertilizer N rates and b) simulated cumulative leached NO_3^- (kg NO_3^--N ha^{-1}) for the four fertilizer N rates and for ridges and furrows separately during the radish growth period of 75 days. Daily leached NO_3^--N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

4 Discussion

4.1 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. 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.

4.2 N retention and NO_3^- 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. Beside of the primary radish root, the spreading root system of radishes is only weakly developed with dominating short fine roots. These conditions also implicate that the fertilizer, which is distributed in the furrows, is most likely dispensable and irreversible lost for root water uptake. Another potential reason might be the 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 consequently 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 NO_3^- concentrations of the seepage water were stronlgy diluted by the substantial rainfall.

4.3 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 to 64% of the irrigation (Lamm and Manges 2000; Saffigna et al. 1976; Steiner et al. 1983) and 4 to 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, its development, and weather conditions (Leistra and Boesten 2008). Considering the morphology of radish leafs, 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 ($\geq$ 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 event.

4.4 ^{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^--N were expressed in relation to applied fertilizer NO_3^--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 NO_3^--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 Munoz 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

5 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^-

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 did therefore 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 NO_3^--N ha^{-1}; 2) applying fertilizer N in 3 to 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 NO_3^--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 proccesses in the plastic-mulched ridges and the subsequent N fate in those ridges to further adjust the management strategies.

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Chapter 4 Modeling water flow in a plastic mulched ridge cultivation system on hillslopes affected by South Korean summer monsoon

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Abstract

Intensive agricultural land use in combination with heavy rain storm events during the summer monsoon season plays a key role in groundwater pollution by nutrients and agrochemicals in agricultural catchments in South Korea. A widespread measure for weed control in this region is plastic mulched ridge cultivation. However, it is not well understood, how and to which extent the water flow regime in sloped fields is hereby modified. To evaluate the effect of plastic mulched ridge cultivation (RT_{pm}) on soil water dynamics, we carried out a two-dimensional process-based modeling study using the numerical model Hydrus 2/3D. Subsequently, RT_{pm} was compared to model simulations of ridge cultivation without plastic cover (RT) and flat conventional tillage without ridges and without plastic cover (CT). Datasets of soil water potentials obtained by field measurements at two plastic mulched potato fields (*Solanum tuberosum L.)* provided the basis for optimizing soil hydraulic parameters inversely by the Levenberg-Marquardt algorithm. We found, that plastic mulching induced horizontal pressure head gradients and forced soil water to move laterally from furrows to ridges under normal weather conditions. During monsoon events, soils were fully saturated and interflow occurred in coarse textured and ploughed topsoil. Further, the water balance of the different model scenarios showed that plastic mulching reduced drainage water up to 16% but concurrently increased the surface runoff up to 65%. The consequences are an increase in runoff peak flow, flood risk and erosion. Therefore, we recommend the application of perforated and biodegradable plastic mulch in regions affected by summer monsoon.

Keywords: Polyethylene film, ridge-furrow tillage, extreme rain events, Hydrus 2/3D, potato crop, hillslopes

1 Introduction

Agricultural management practices, soil properties and field topography lead to a high variability in soil water movement, solute transport and leaching of nutrients and agrochemicals. In South Korea, ridge tillage with impermeable black plastic mulch covering the ridges is the most common practice for dryland crops such as radish (*Raphanus sativus*), cabbage (*Brassica rapa susp. Pekinensis (lour.), Hanelt, Brassica aleracea convar. Capitata var. alba*), beans *(Glycine max. (L.) Merr.)* and potatoes *(Solanum tuberosum L.),* which are predominately grown on slopes. Intense fertilization together with heavy rainfalls during summer monsoon season poses a high risk of groundwater pollution in the Haean catchment. Additionally, the discharge of phosphorus associated with sediments from agricultural areas causes eutrophication and deterioration of water quality in downstream reservoirs in South Korea (Kim et al., 2001). This is of major significance because the river system of Haean contributes to the Soyang Lake, which is a major source of freshwater for the metropolitan area of Seoul.

The effect of flat row-interrow cultivation on soil water dynamics was investigated for soybean and corn crops in previous studies (Timlin et al. 2001, van Wesenbeeck and Kachanoski, 1988, Paltineanu and Starr, 2000). The findings showed increased soil moisture in row positions due to interception and stemflow. The same effect was also found for potato crops cultivated in ridges (Saffigna et al., 1976), but with the addition of concurrently higher water contents in furrows because of surface runoff from ridges and leaf drip from the outer foliage. Soil and plant biological effects of the plastic mulch were studied by Gürsoy et al. (2011) and Laszlo and Gyuricza (2004), who found favorable physical soil conditions and improved growth and yield of maize and corn crops. Previous research on plastic mulched ridge cultivation focused mainly on rain water harvesting in combination with irrigation techniques in semiarid and arid regions, in which the plastic covered ridges induce runoff to the planted furrow area, leading to an increased crop yield and water availability (Wang et al. 2008, Li and Gong 2002, Li et al., 2008, Tian et al., 2003; Mahajan et al., 2007). In contrast, dryland crops in South

Korea are planted in the plastic covered ridges to suppress weed growth and to support early plant emergence due to increased soil temperature in the ridges.

Only a few modeling studies about ridge cultivation systems exist. Solute transport of pesticides in an irrigated potato ridge cultivation system was investigated by Leistra and Boesten (2010). They demonstrated that the risk of pesticide leaching in furrow soil can be substantially higher than in corresponding level field soil. Abbasi et al. (2004) simulated water flow in a long furrow system with furrow irrigation using Hydrus 2/3D to estimate inversely soil hydraulic properties and transport parameters. Dusek et al. (2010) used the S1D and S2D models to simulate water flow and solute transport in a drip irrigated plastic mulched pineapple cultivation.

Since there are no modeling studies about plastic mulched ridge cultivation in mountainous areas affected by extreme rain events, the aim of this study was to evaluate the effect of plastic mulched ridge cultivation on soil water dynamics under a summer monsoonal climate. Therefore, we used a monitoring network of tensiometers and FDR sensors in two potato fields in the mountainous Haean basin in South Korea to observe soil water dynamics in ridge and furrow positions. The field data sets of standard tensiometers were used to estimate soil hydraulic parameters using an inverse modeling approach based on Levenberg-Marquardt nonlinear minimization algorithm. Subsequently we used the optimized parameters of the water flow model to run scenarios regarding ridge tillage without plastic mulch and flat conventional tillage. The comparison of plastic mulched ridge tillage (RT_{pm}), ridge tillage without plastic coverage (RT) and a flat conventional tillage (CT) allows a better understanding of soil water dynamics and water movement influenced by the plastic mulch.

2 Materials and Methods

2.1 Study area

The agriculturally used Haean catchment is located in Gangwon Province in the North-eastern part of South Korea (Fig.1). While rice paddies are dominating in the flat

parts of the basin, dryland farming is practiced in the hillsloped areas of the catchment. The annual precipitation sum in Haean basin is about 1577 mm (11-years average) with 50-60% of the annual rainfall occurring during summer from June to August. The Korean peninsula is characterized by two rainfall peaks, one in July and one in August. The maximum rainfall, however, shifted in the recent decades from July to August (Lee et al., 2010). The precipitation during the 2010 observation period is shown in Fig.3.
Plastic mulched ridge cultivation is the common practice to cultivate dryland crops in Haean Catchment. Ridges (35 cm width and 15 cm height) are covered with an impermeable black polyethylene film and alternate with uncovered furrows (35 cm width). Planting holes (diameter 5 cm) in the plastic cover are located at the top of the ridges with a plant-to-plant spacing of 25 cm. Cambisols developed on the granitic bedrock material are widespread over the catchment. Due to high erosion rates, however, the application of sandy soil material before the growing season is a commonly used method to compensate for soil loss. Thus, highly disturbed soil profiles are characterized by light-textured, permeable and ploughed top layers, which are prone to nutrient and pesticide leaching and subjacent B horizons.

Measurements were carried out at two different potato fields (*Solanum tuberosum L.*) within the Haean Catchment, each with plastic mulched ridges and similar planting dates as well as slope degrees. The average slope gradient was 11° and 10° at field site 1 and 2, respectively. Seed p otatoes were planted on 5 May at field site 1 and on 10 May at field site 2. Plastic coverage caused higher temperature in soils and therefore crops emerged rapidly. At both field sites plants emerged before the first measurement day (31 May 2010). Mineral fertilizer was applied as granules and mixed into the topsoil layer before ridges were built. During the observation period pesticides were sprayed twice throughout the field sites. Field site 1 was characterized by a granitic bedrock layer at 1 m depth. At field site 2 the soil was deeper developed and the underlaying bedrock layer could not been detected by excavation down to 130 cm. Soil physical properties of the experimental sites are given in Table 1.

Table1
Soil physical properties of the experimental sites

	Horizon (WRB)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Soil texture class (USDA)
Field site 1	Ap	65.72	26.78	7.50	1.28 (±0.02)	Sandy loam
	Bw	39.30	51.60	9.10	1.18 (±0.05)	Silt loam
Field site 2	Ap	42.65	41.15	16.20	1.27(±0.04)	Loam
	Bwb	22.00	52.90	25.10	1.31(±0.03)	Silt loam

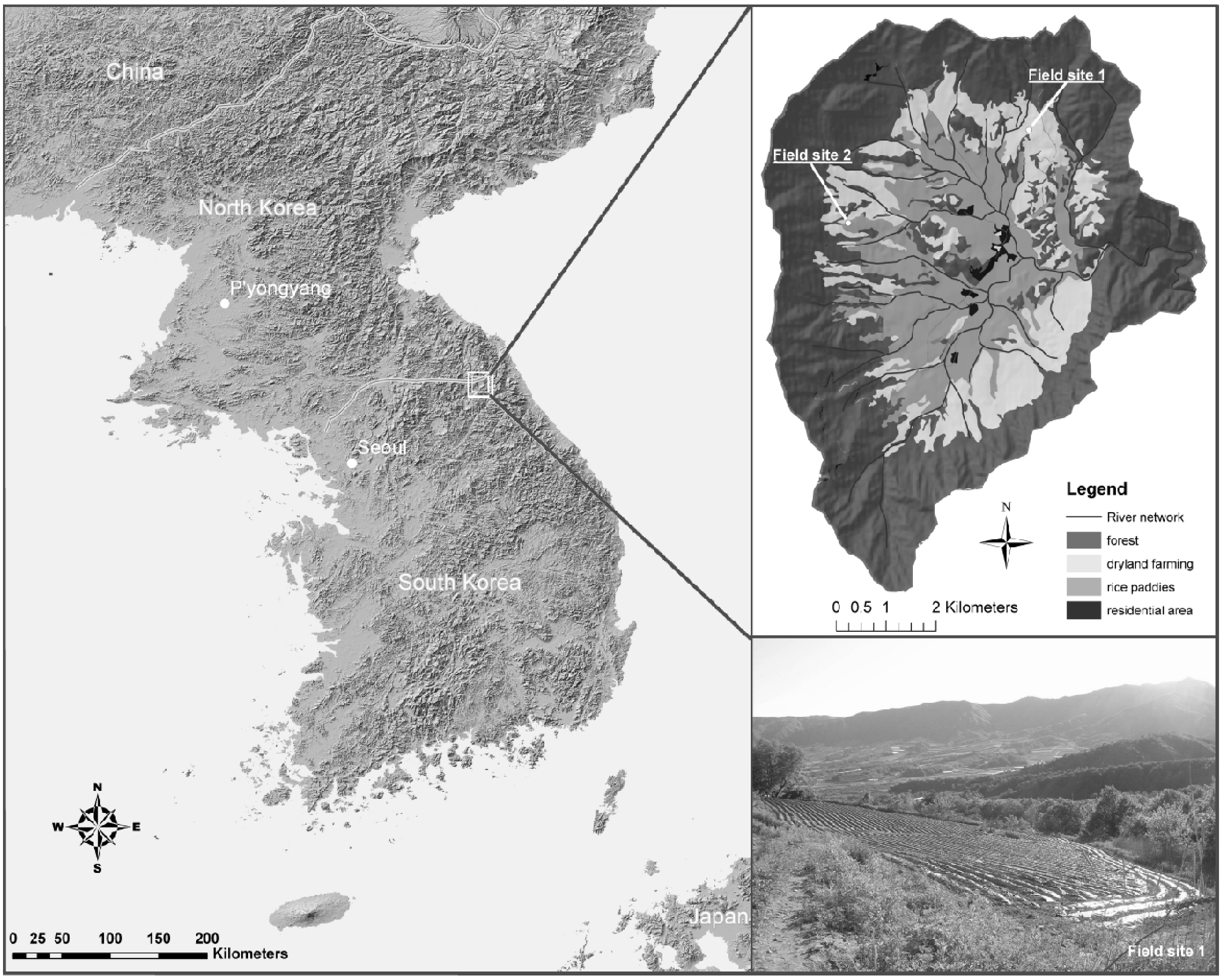

Fig. 1. Topographical map of South Korea (left), land use map of the Haean Catchment (top right) and picture of field site 1 (bottom right).

2.2 Field measurements

A field monitoring network of standard tensiometers, continuously recording tensiometers and FDR sensors (Decagon 10HS moisture sensors at 15 and 30 cm depths, DeltaT ThetaProbe ML2X in 60 cm depths) was set up in the two potato fields on hillslopes on 28 May 2010. At each field site we installed the sensors in three subplots accounting for different slope position (upper, middle and lower slope). In each ridge and each furrow, monitoring devices were installed at 15, 30 and 60 cm depth from the respective soil surface. The location of the respective depth in a ridge or furrow was chosen randomly. The distance between sensors in ridges and furrows was 2 m. All FDR sensors and continuously recording tensiometers were connected to a DeltaT logger, which logged soil water contents and soil water potential in a 30-min interval. Standard tensiometers were read out with a manual pressure reader in a 2-d interval from 31 May to 24 August, 2010. We used only the standard tensiometer data sets for the modeling approach to run simulations on a daily time step. The design of the monitoring set up at both field sites is shown in Fig.2.

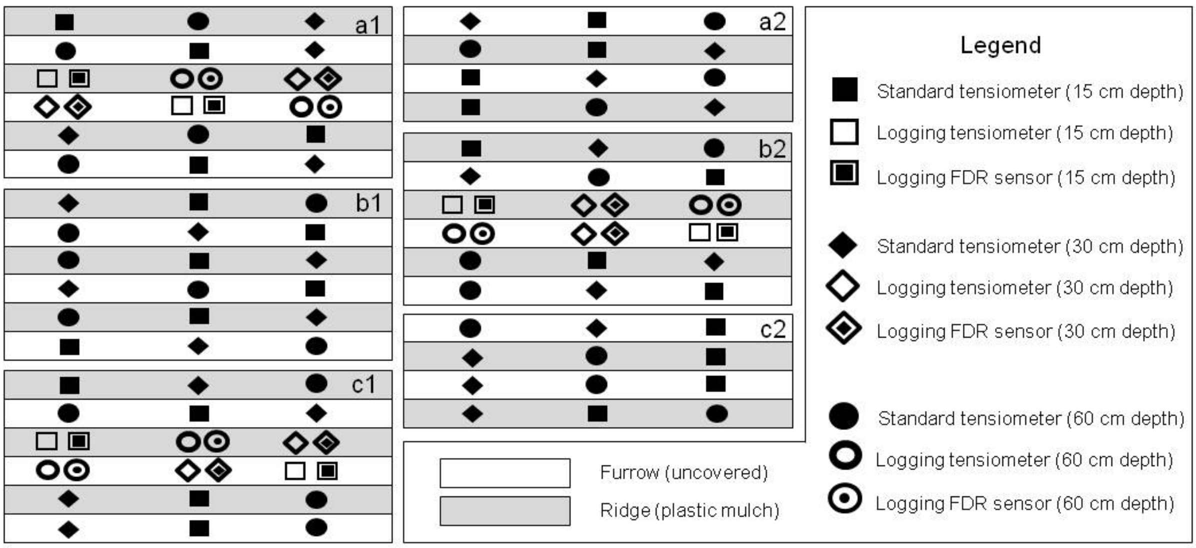

Fig. 2. Monitoring network of standard tensiometers, continuously recording tensiometers and FDR sensors; subplots a, b and c refers to different slope locations (a: upper slope, b: middle slope, c: lower slope), 1: field site 1 and 2: field site 2. The distance between subplots was approximately 15 and 30 m on field site 1 and 2, respectively.

2.3 Modeling approach

2.3.1 Governing flow equations

The ability of representing physical processes such as subsurface water flow in variable saturated media is an advantage of process-based numerical models. Previous tracer studies at the selected field sites (unpublished) have shown that preferential flow paths were negligible for soil water movement. Such uniform flow processes can be described using the Richards' equation. Based on the Galerkin finite element method, Hydrus 2/3D solves the Richards' equation for two-dimensional water flow in a variably saturated porous media. The extended Richards' equation incorporates a sink term, which considers the water uptake by roots (Eq.1). All following equations are described in Šejna et al. (2011).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S \qquad (1)$$

where θ is the volumetric water content (cm³ cm^{-3}), h is the pressure head (cm), S is a sink term (cm d^{-1}), x_i $(i=1,2)$ are the spatial coordinates (cm), t is time (days), K_{ij}^{A} are components of a dimensionless anisotropy tensor K^{A}, and K is the saturated hydraulic conductivity function (cm d^{-1}) given by

$$K(h,x,y,z) = K_s\,(x,y,z)\,K_r\,(h,x,y,z) \qquad (2)$$

where K_r is the relative hydraulic conductivity and K_s is the saturated hydraulic conductivity (cm d^{-1}).

The sink term S in (1), represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake. Equation 3 shows the definitions of the sink term S by Feddes et al. (1978)

$$S(h) = \alpha(h)S_p \tag{3}$$

where the water stress response function *α(h)* is a prescribed dimensionless function of the soil water pressure head $(0 \leq \alpha \leq 1)$, and S_p is the potential water uptake rate [day^{-1}]. According to Wesseling et al. (1991) root water uptake of potatoes is assumed to be zero if the flow domain is close to saturation (> -10 cm) and if the pressure head becomes lower than the wilting point (< -16000 cm). Water uptake of potatoes is considered optimal for pressure heads between -25 and -320 cm. Within this range, water uptake decreases (or increases) linearly with h. S_p is equal to the water uptake rate during no water stress when $\alpha(h)$=1. Based on field observations, root water uptake was considered down to 30 cm soil depth.

The unsaturated soil hydraulic properties as well as the hydraulic conductivity are described by the soil hydraulic function model of van Genuchten (1980) in Equations 4 and 5.

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^{1-1/n}} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{4}$$

where $\theta(h)$ is soil water retention, θ_r is the residual water content (cm³ cm^{-3}), θ_s is the saturated water content (cm³ cm^{-3}), α and n are empirical shape parameters.

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{1/1-1/n})^{1-1/n}\right]^2 \tag{5}$$

where $K(h)$ is hydraulic conductivity (cm d^{-1}), K_s is the saturated hydraulic conductivity (cm d^{-1}), l is the pore connectivity parameter, which was estimated to be about 0.5 (Mualem, 1976).

2.3.2 Model parameterization

Two weather stations, both located approximately 750 m from the respective field site, provided daily precipitation data and additional weather parameters for the calculation of soil evaporation and crop transpiration (Fig.3). Due to its exposed position in the catchment, field site 2 received approximately 15-20% more precipitation than field side 1. Precipitation data was multiplied by 2 to include the surface runoff from the plastic mulched ridges. This factor was calculated by assuming a permeable area (furrows and planting holes) of 50% of the total area and a plastic covered area (ridges) of 50% in a two-dimensional profile (Dusek et al., 2010). For the model scenario without plastic mulch, the original precipitation data was used. Soil evaporation and crop transpiration were calculated with the FAO Penman-Monteith equation for potato crops using weather parameters such as solar radiation, air temperature, wind speed, humidity and air pressure, which were measured by the weather stations. A detailed description of the dual crop coefficient approach for separately calculating soil evaporation and crop transpiration is given by Allen et al. (1998).

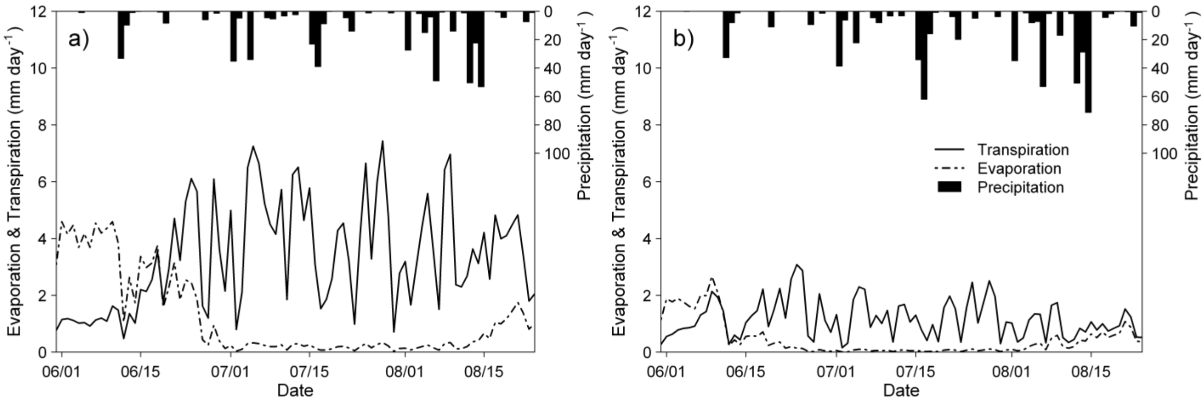

Fig. 3. Daily precipitation, evaporation and transpiration rates during the growing season 2010; a) Field site 1 and b) Field site 2

In Fig.3, soil evaporation and crop transpiration for both field sites are given separately. Different weather, soil and management conditions at field site 2 lead to lower evaporation and transpiration rates compared to field site 1.

The Van Genuchten parameters saturated and residual water content θs and θr, α and n and the saturated hydraulic conductivity (K_{sat}) were initially estimated based on texture and bulk density using the neural network pedotransfer functions of Rosetta lite module (Schaap et al., 2001), which is implemented in Hydrus 2/3D. Inverse estimation of soil hydraulic properties are based on time series datasets of pressure heads, which we read out with standard tensiometers. We ran the simulations on a daily timestep with 264 data points in the objective function, which equates 44 pressure head values at each observation point in the model. These 44 pressure head values at each observation point in the model (e.g. Ridge 15 cm depth) represented the calculated mean of 7 and 6 tensiometers, which were installed at the same depth (e.g. 15 cm soil depth) and same location (e.g. ridge) at field site 1 and field site 2, respectively. As a first step we fitted the soil hydraulic parameters θr and θs. Afterwards α, n and K_{sat} were optimized simultaneously. The optimization approach was based on Levenberg-Marquardt non-linear minimization method. Initially estimated soil hydraulic parameters and α, n, θs and θr and the saturated hydraulic conductivity K_{sat} for both field sites are given in Table 3.

2.3.3 Initial & Boundary Conditions

Pressure head values measured on 31 May 2010 reflecting the beginning of the observation period (31 May to 24 August 2010) were used to adjust the initial conditions in the water flow domain. Surface boundary conditions were set to atmospheric conditions in furrows and planting holes, whereas plastic mulched areas were set to no flux conditions (Fig.4). For the scenarios without coverage of the ridges (RT) and flat conventional tillage (CT) atmospheric boundary conditions were applied to the entire surface boundary. Although the diameter of the planting holes was in fact 5 cm, it was necessary to scale it down to 1 cm width in the two-dimensional model in order to keep the correct dimension, when calculating e.g. drainage water fluxes per m². The upper left hand boundary was set to no flux, which marks the transition from the plowed agricultural field to a compacted farm track. The bottom boundary was defined as no flux conditions (field site 1) due to granite parent rock in 1 m depth. At field site 2, free drainage conditions were applied to the bottom boundary, because a soil excavation showed a deeper soil development than 1 m depth. The lower right hand boundary was defined as seepage face. For the calculation of water fluxes at the transition from ridges to furrows and vice versa, meshlines (F1-3 & R1-3) were included in the model. Meshlines F1-3 reflect water fluxes coming from furrows but contribute to ridges. In contrast, meshlines R1-3 represent the transition from ridges to furrows in slope direction (Fig.4).

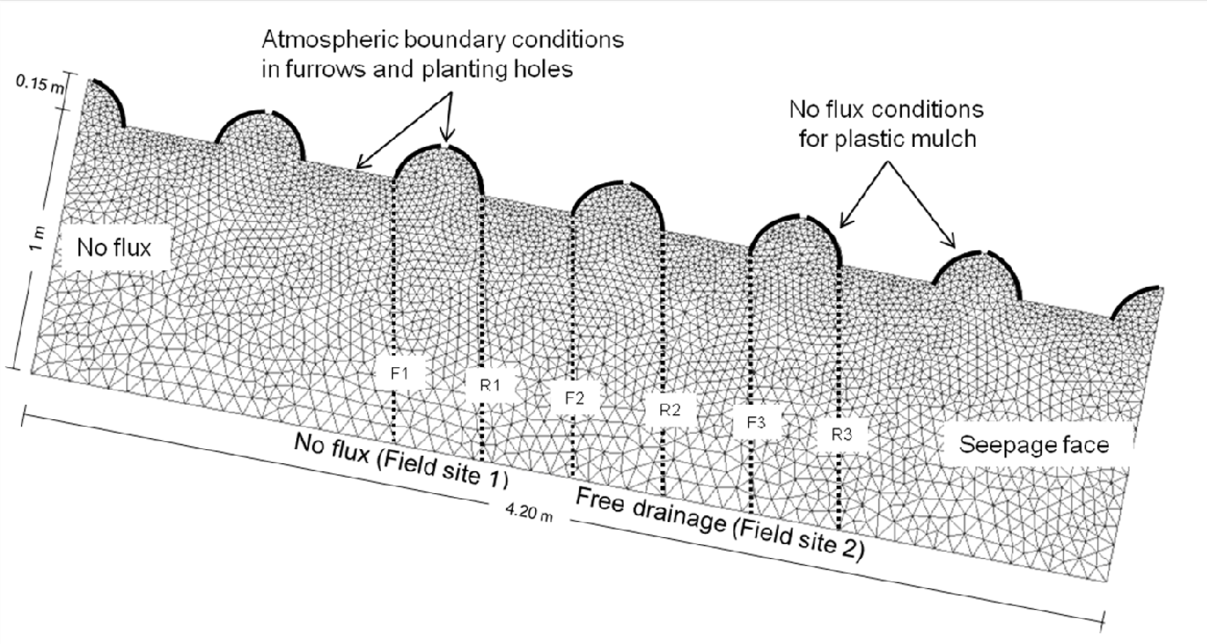

Fig. 4. Boundary conditions of the model simulations; note that the bottom boundary varies between the two field sites; vertical meshlines F1-3 and R1-3 were included to calculate lateral water fluxes (see Fig.9); for simulation of ridges without coverage (RT) and conventional tillage (CT) atmospheric boundary conditions were implemented at the entire surface.

2.3.4 Model evaluation statistics

Different statistical techniques such as Pearson's correlation coefficient (R), coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), model bias ($\bar{e}$) and percentage bias (Pbias) were used to evaluate the models. A comprehensive overview of the evaluation statistics for hydrological models is provided by Moriasi et al. (2007).

Pearson`s correlation coefficient and the coefficient of determination range from 0 to 1, where 1 indicates a perfectly linear relationship. The Nash-Sutcliffe coefficient (Eq. 6) determines the relative magnitude of the residual variance compared to the observed data variance. The coefficient of efficiency varies between -∞ and 1, where 1 indicates a perfect model. Model performance is unacceptable when the value is < 0.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right] \tag{6}$$

where Y_i^{obs} is the *i*th observed pressure head value, Y_i^{sim} is the *i*th simulated pressure head value and Y^{mean} is the mean of observed pressure head values.
McCuen et al. (2006) noted that NSE values also depend on sample size, bias of magnitude and outliers. Therefore he recommended reporting always the bias (Eq.7, in the unit of the variable) along with the NSE, which is computed by

$$\bar{e} = \frac{1}{n}\sum_{i=1}^{n}(Y_i^{sim} - Y_i^{obs}) \tag{7}$$

The percentage bias (Pbias) is easier to interpret and is determined by the ratio of the bias ē to the mean of the measured values (Y^{mean}) multiplied by 100. In the case of soil water potentials (negative values), a negative percentage bias indicates higher simulated pressure heads in comparison to observed pressure heads.

2.3.5 Sensitivity analysis

Dynamic root development is not implemented in the Hydrus2D. Therefore we assumed based on field observations an average rooting depth of 30 cm during the entire simulation period for the model fitting procedure. Plant development to adult stage occurred relatively quickly within approximately four weeks after emergence.

Within this time period the differing spatial distribution of roots in the soil has an effect on root water uptake and soil water status. We analysed the sensitivity of the water balance components such as seepage, runoff and drainage water fluxes to differing rooting depths by varying the root depth from 10 cm to 60 cm in an interval of 10 cm.

Although the calculation of the FAO56 dual crop coefficients includes actual weather data information, the estimation of evaporation and transpiration rates is empirical and only an approximate determination. We additionally applied a sensitivity analysis of the water balance by changing the evaporation and transpiration rates inputs. Thus we maintained the original calculated ratio of evaporation and transpiration but varied both rates in percentage terms. Therefore we increased the original calculated values up to 100 %. Accordingly we reduced the evaporation and transpiration rates to 0 %. The sensitivity analysis regarding both, root development as well as evaporation and transpiration rates was accomplished for all surface managements RT_{pm}, RT and CT.

3 Results

3.1 Model evaluation and parameter optimization

The comparison between observed and simulated pressure heads (Fig.5) showed a good agreement at field site 1, whereas the agreement at field site 2 was less satisfactory. While, wetting events in particular were simulated reasonably well, the low pressure heads during drying cycles at the beginning of the observation period were underestimated, especially at field site 2. The evaluation coefficients for both field sites are given in Table 2.

Table 2
Model evaluation coefficients R, R^2, Nash-Sutcliffe efficiency (NSE), bias ($\bar{e}$) and percentage bias (Pbias) for simulations of both field sites

	R	R^2	NSE	$\bar{e}$	Pbias
Field site 1	0.89	0.79	0.79	-1.78	2%
Field site 2	0.76	0.58	0.48	-13.10	12%

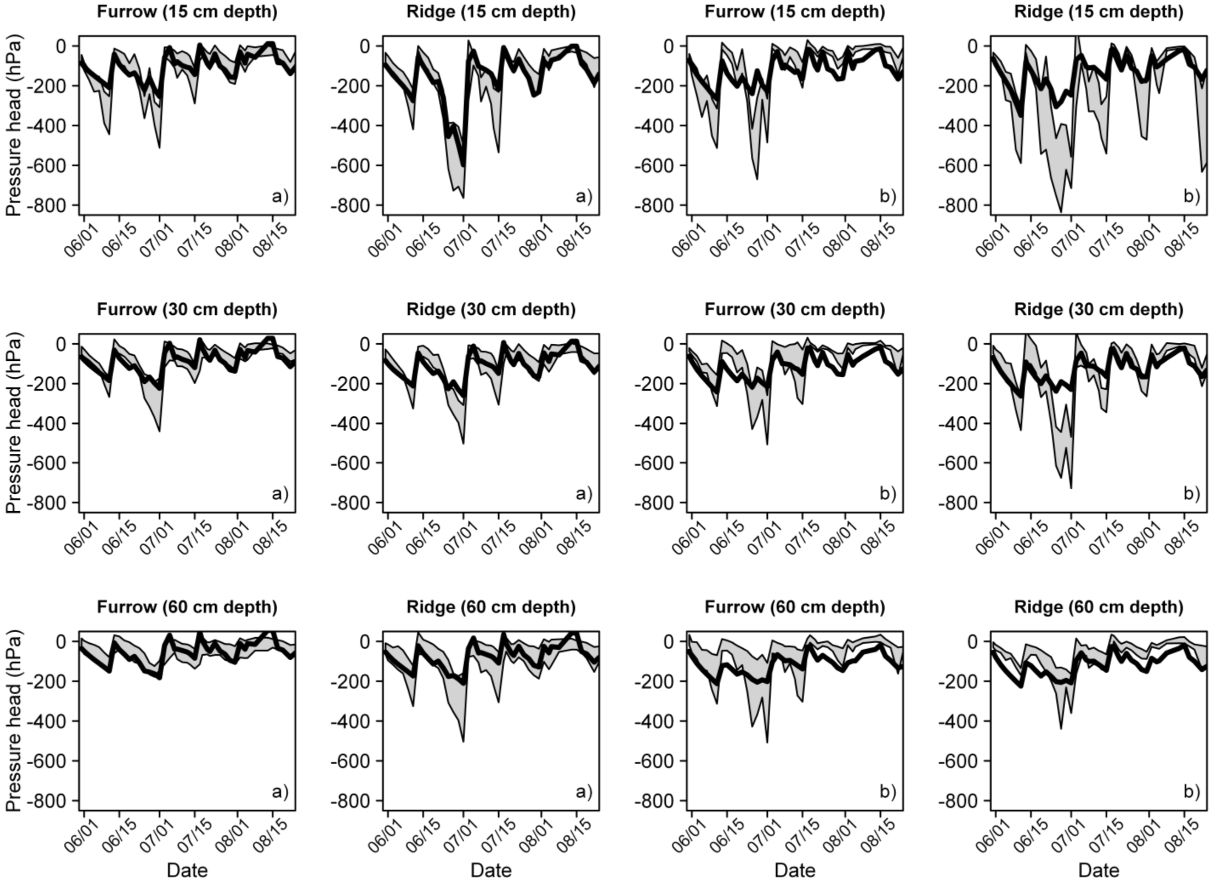

Fig. 5. Observed vs. simulated pressure heads at different depth for a) Field site 1 and b) Field site 2; limits of grey area = +/- standard deviation of the observed data, black solid line = simulated pressure heads.

The optimization of the water retention parameters (Table 3) showed an initial overestimation of the saturated water content θs, while the residual water content θr was underestimated. The n values, which configure the steepness of the water retention curves, were smaller as initially estimated, resulting in a flatter curve characteristic for all horizons at both field sites. Therefore, the water holding capacity was higher in all four horizons and drainage occured within a wider range of pressure heads. The saturated hydraulic conductivity K_{sat} changed to lower values in the subjacent B-horizon at field site 1 and in both horizons at field site 2.

Table 3
Initial estimates (est.) and optimized (opt.) van Genuchten parameters and saturated hydraulic conductivity (K_{sat}) for both field sites

		θr ($cm^3\ cm^{-3}$)		θs ($cm^3\ cm^{-3}$)		α (cm^{-1})		n (-)		K_{sat} ($cm\ day^{-1}$)	
		est.	opt.	est.	opt.	est.	opt.	est.	opt.	est.	opt.
Field site 1	**Material 1**	0.0402	0.071	0.4217	0.313	0.0266	0.046	1.452	1.408	102.9	103.0
	Material 2	0.0471	0.138	0.4121	0.346	0.0057	0.006	1.641	1.2	81.94	29.4
Field site 2	**Material 1**	0.0574	0.134	0.419	0.301	0.0082	0.014	1.566	1.403	31.02	2.9
	Material 2	0.0767	0.004	0.443	0.393	0.0065	0.006	1.599	1.2	19.13	15.4

3.2 Soil water dynamics

Fig.6 shows the pressure heads and water contents in the flow domain on day 21 of the simulation period (June 20, 2010) of the growing season. After a dry period of one week, a rain event with 8.4 mm and 11 mm at field site 1 and field site 2, respectively, occurred on this day. Pressure heads in the top layer and in ridge positions are lower than in comparable furrow positions under RT_{pm} and RT, indicating that the soil is drier due to intense water uptake by plants during the main growing stage. Differences in pressure heads in the top layer between ridges and furrows are about -70 to -100 cm at field site 1, whereas pressure heads at field site 2 differ between -200 and -40 cm. At both field sites, pressure head gradients are distinct horizontally, which forces soil water to flow laterally from the furrows to the ridges. At field site 1, where the soil texture changes between the A- (Sandy loam) and B- (Silty loam) horizon, the differences in pressure heads between ridge and furrow positions and the resulting horizontal water flow is only characteristic for the A-horizon. In the subjacent B-horizon the effect of RT_{pm} and RT on pressure heads is negligible. At field site 2, where the A- (Loam) and B- (Silt loam) horizon are fine-textured, the differences in pressure heads are distinct even in deeper soil layers. Water flow from furrows to ridges due to almost horizontal pressure head gradients was observed down to 50- 60 cm soil depth. Under conventional tillage, pressure head gradients are distinct vertically to the soil surface at both field sites, which causes a main vertical water flow from the top layer to the sublayer. The differences in pressure heads between the top layer and the sublayer are small at field site 1, whereas at field site 2 differences range between -40 and -160 cm. Although, the simulation of day 21 represents soil hydraulic conditions after a dry period of seven days, the B-horizons at both field sites are characterized by a high water content ranging between 0.32 $cm^3\ cm^{-3}$ and 0.36 $cm^3\ cm^{-3}$. Due to an extreme rain event at day 13 and 14 of the simulation with a total amount of precipitation of 43 mm at field site 1 and 33.4 mm at field site 2, drainage processes occurred very slowly due to the finer soil texture of the subsoils.

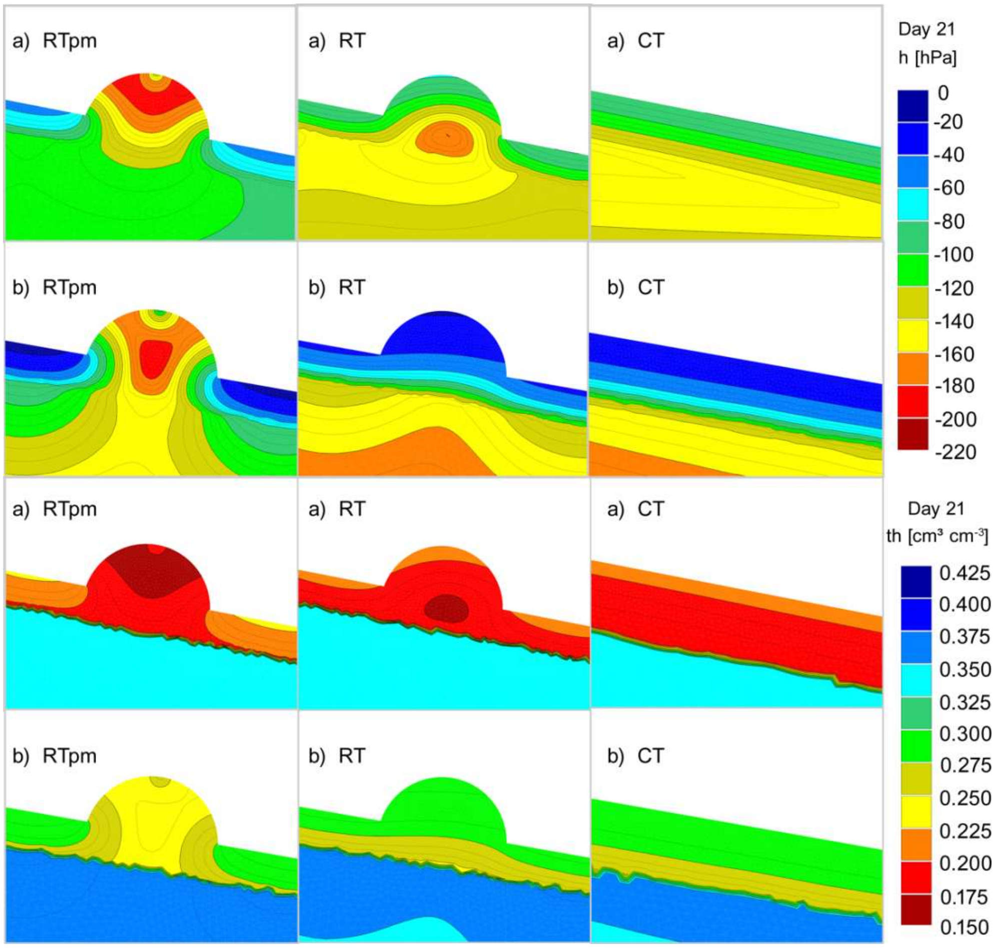

Fig. 6. Pressure head (h) and water content (th) under different management strategies at day 21 for both field sites

In comparison to the dry conditions, Fig. 7 represents soil hydraulic conditions in the flow domain during a monsoon event on simulation day 75 (August 13, 2010) with a total precipitation amount of 50.4 mm and 50.6 mm at field site 1 and field site 2, respectively. The comparison of pressure heads under the different management strategies at field site 1 shows no discrepancy in pressure heads between the ridge and the furrow positions due to the high hydraulic conductivity K_{sat} in the A-horizon. The soil water is quickly and homogeneously distributed in the soil volume. Pressure head gradients are distinct vertically in the soil profile. However, the effect of plastic mulching on pressure heads during a monsoon event is more evident at field site 2. Due to a lower hydraulic conductivity in the top layer, soil water distribution occurs more slowly compared to field site 1 and a part of the soil remains unsaturated below the plastic film in the top layer as well as in the sublayer of the ridges. RT leads to a more homogeneous infiltration, resulting in a saturated B-horizon and in isolines, which are distinctly parallel to the soil surface.

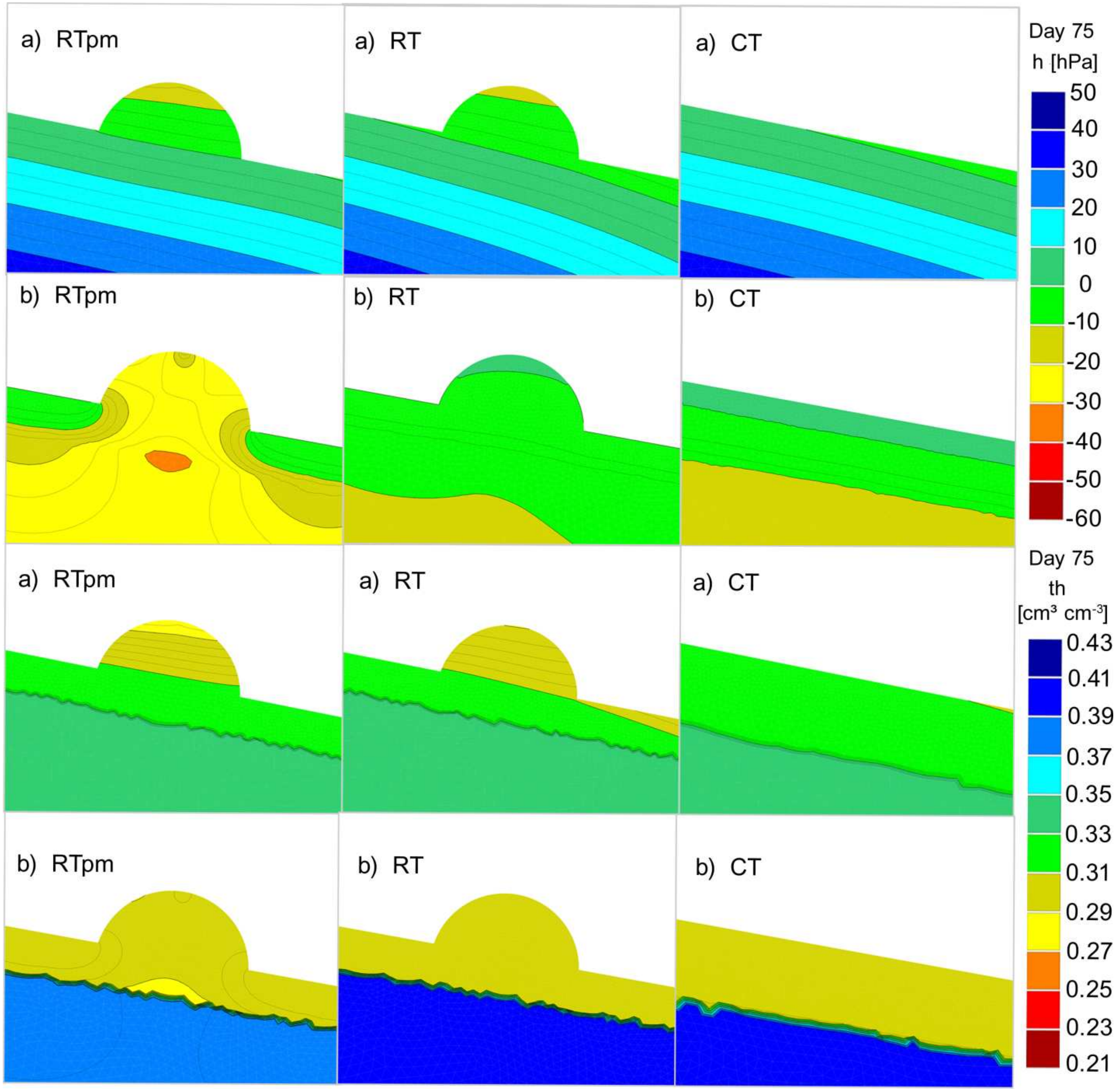

Fig. 7. Pressure head (h) and water content (th) under different management strategies at day 75 during a monsoon event for both field sites

The simulation showed higher pressure heads at the beginning and at the end of the growing season in the furrow positions, which reflects a smaller transpiration rate in the initial phase of the plant development and in the senescence stage before harvesting, when most of the aboveground plant parts had already died. Smaller transpiration rates coincide with higher evaporation rates resulting in a reversed water flow directed from the ridges to the furrows. However, these simulation results could not be confirmed by field observations. On the contrary, the field measurements revealed that pressure heads in the ridge positions were lower at the beginning as well as at the end of the growing season than in the furrow positions.

3.3. Flow velocities

Fig.8 shows the effect of tillage management on flow velocities at both field sites. Affected by the bottom boundary conditions, main flow direction is aligned laterally at field site 1 caused by the granite layer at 1 m depth. Field site 2, however, shows a vertical flow direction representing a deeper developed soil. At field site 1, the coarser soil texture of the top layer and the high saturated hydraulic conductivity of 103 cm d^{-1} implicate high flow velocities and interflow above the finer textured subsoil. The bottom of the ridges is only slightly affected by the high velocities. Protected by the plastic coverage, velocities in the entire ridge area are < 8 cm d^{-1}, while the soil water velocities in the top layer below the ridge are 4 to 6-times higher. In general, flow velocities are increasing in slope direction. The flow velocities found at the field site 2 are generally lower than at field site 1. Due to similar low saturated hydraulic conductivities as well as similar soil texture in the A- and B-horizon at field site 2, the layer border does not act as an interflow basis. Highest flow velocities (~10 cm d^{-1}) are reached at the transition from furrows to ridges. Plastic mulching induces low flow velocities (0-1.6 cm d^{-1}) in the ridge area down to 50 cm depth (from top of the ridge surface).

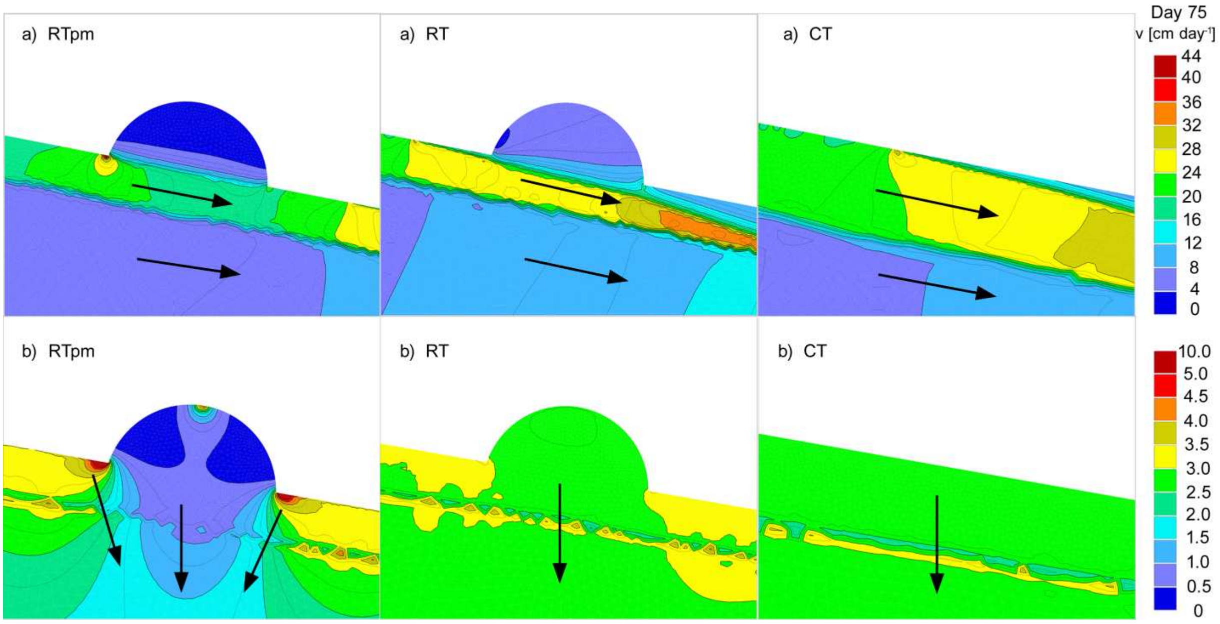

Fig. 8. Flow velocity during a monsoon event (day 75) under different management systems at field site 1 and field site 2, black arrows indicate the main flow direction.

3.4. Water fluxes

To investigate the effect of the different management strategies on water fluxes, cumulative water fluxes at the transitions from furrows to ridges as well as at the transition from ridges to furrows were determined (Fig.9). Depending on unequal bottom boundary conditions, cumulative water fluxes varied strongly between both field sites due to different dominant flow directions. At field site 1, where subjacent granite bedrock material forced water to move laterally in slope direction, plastic mulching led to a reduction of water fluxes, whereas water fluxes in simulations without coverage and with a flat surface were high. However, the total amount of water fluxes at R3 after the simulation period only differed slightly between management strategies. In contrast to field site 1, water percolated at the bottom boundary of field site 2, which induced a main vertical water movement, resulting in positive water fluxes at the transition from furrows to ridges and negative water fluxes at the transition from ridges to furrows in slope direction as a result of lower pressure heads below the plastic coverage. Without coverage (RT) the effect was diminished. Under conventional tillage (CT) all values were negative representing the high influence of free drainage conditions at the bottom.

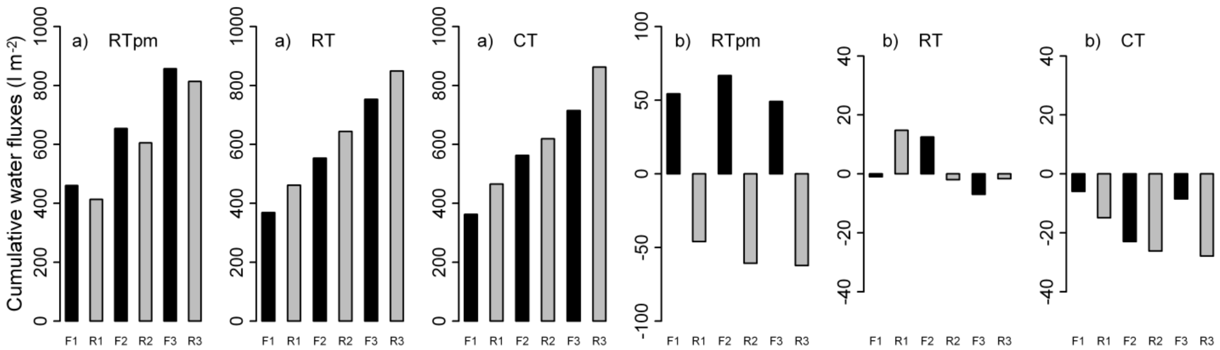

Fig. 9. Cumulative water fluxes at the transition from furrows to ridges (F1-3) and from ridges to furrows (R1-3) in slope direction, see also the graphical implementation in Fig.4. Due to different bottom boundary conditions at both field sites, only positive cumulative water fluxes are simulated at field site 1 due to mainly lateral water movement, at field site 2 the main vertical water movement results in positive and negative water fluxes; a) field site 1, b) field site 2

The water balance of the calibrated model with cumulative water fluxes in and out of the flow domain after the simulation period of 86 days is shown in Table 4. The water balance error of all simulations was considerably low (< 0.5%). As mentioned before, the differing boundary conditions of both field sites resulted also in large differences in the cumulative water fluxes. At field site 1*seepage* was the only subsurface outflow and the bottom boundary of the model was set to no flux conditions (granitic bedrock). This combination strongly supported the lateral subsurface downhill flow resulting in high seepage water fluxes. In contrary, the bottom boundary of field site 2 was defined as a free *drainage* boundary (deeper developed soil), which resulted in a dominating vertical water movement and therefore in high cumulative drainage water fluxes compared to seepage. The *runoff* was calculated by the amount of water, which ponded theoretically at the surface when the infiltration capacity was exceeded. The difference in runoff rates between both field sites was caused by varying saturated hydraulic conductivities. The *transpiration* and *evaporation* rates differed between both field sites because the potential evaporation and transpiration was calculated based on differing weather stations (Fig.3). Since the potential evaporation and transpiration rates were already low due to a very high average humidity (average humidity of 75% for field site 1 and 91 % for field site 2), the actual transpiration rates was determined by the potential ET rates and the soil water status. When the soil was saturated or near saturation in the monsoon season, the root water uptake became zero (Eq.3). The initial and final water content of both field sites were comparable, so that the change in *water storage* was very low after the simulation period of 86 days.

The comparison among the tillage treatment showed that seepage water was lowest under RT compared to RT_{pm} and CT at field site 1, while the lowest seepage water amount was characteristic for RT_{pm} at field site 2. The simulation at field site 1, however, showed that the differences in seepage water amount were almost negligible, only the flat conventional tillage led to higher amounts of seepage water. Drainage water at field site 2 was about 16% higher without coverage than with coverage. The evaporation rate was 40% higher without coverage at field site 1 and 48% at field site 2, respectively. The transpiration, however, did not vary across the different management strategies. As expected, plastic mulching increased surface runoff. Low runoff rates at field site 1 reflected the high saturated hydraulic conductivity (103 cm d^{-1}) in the top soil. At field site 2, surface runoff was reduced to 65% under RT compared to RT_{pm}.

Table 4
Water balance of the model flow domain after the simulation period of 86 days

		P	$WC_{initial}$	WC_{final}	T	E	S	R	D	rel.err (%)
Field site 1	RT_{pm}	20.03 (992)	14.37 (324)	13.96 (315)	5.82 (141)	1.69 (41)	12.65 (1183)	0.15 (4)	-	0.33
	RT	20.49 (992)	14.37 (324)	13.83 (312)	5.79 (140)	2.78 (67)	12.23 (1143)	0.044 (1)	-	0.49
	CT	20.49 (992)	14.28 (321)	13.71 (308)	5.80 (140)	2.63 (64)	12.79 (1306)	0.029 (1)	-	0.47
Field site 2	RT_{pm}	23.85 (1178)	16.81 (379)	15.22 (343)	2.06 (50)	0.64 (15)	0.002 (0)	7.66 (185)	14.99 (367)	0.23
	RT	24.39 (1178)	16.81 (379)	15.18 (342)	1.99 (48)	1.21 (29)	0.094 (8)	4.98 (120)	17.76 (434)	0.03
	CT	24.39 (1178)	16.77 (377)	15.11 (340)	2.00 (48)	1.11 (27)	0.015 (1)	5.56 (134)	17.30 (408)	0.19

RT_{pm}: Ridge tillage with plastic mulch; RT: Ridge tillage without plastic mulch; CT: Conventional tillage with a flat surface; note that seepage is the only outflow of the flow domain at field site 1 and free drainage is the bottom boundary only at field site 2. P: Precipitation (varies between treatments because of differing atmospheric boundary lengths), $WC_{initial}$: initial water content (varies between treatments because of differing model volumes), WC_{final}: final water content, T: Transpiration, E: Evaporation, S: Seepage, R: Runoff, D: Drainage, rel. err.: Relative error of the water balance; All values are given in liter and related to the xyz-dimension of the model, the values in braces are associated to an area of m² for P, T, E, S, R, D and to a volume of m³ for $WC_{initial}$ and WC_{final}

3.5 Sensitivity analysis

A dynamic root development is not implemented in the Hydrus2/3D model so that the impact on water balance outputs by increasing root water uptake in the first stage of growth could not be captured. Therefore, we analysed the impact of differing rooting depths on cumulative water fluxes such as seepage, drainage, runoff and water storage by varying the rooting depth from 10 cm to 60 cm (Table 5). As expected, with increasing rooting depth the cumulative drainage water fluxes decreased under all tillage management systems due to an increased root water uptake. Furthermore, the increased root depth led to a decrease in seepage water only at field site 1, while the seepage water at field site 2 was consistent. The cumulative runoff did not show a clear trend. At field site 1seepage water was mostly affected by changes of rooting depth, however, the overall change in seepage water and the influence on water balance was estimated to be low. This was also true for the water balance outputs of field site 2, where cumulative drainage, seepage and runoff water fluxes at the end of the simulation period of 86 days showed only marginal changes as affected by differing rooting depths. Water storage was less after the simulation period, however, the varying rooting depths influenced the change in water storage only marginal. In general, the water balance outputs were robust against varying rooting depths. Further, the ratio between different treatments was also relatively robust. The cumulative runoff under RT at field site 1 was between 64 - 74 % less compared to RT_{pm} under varying rooting depth. The difference in runoff between CT and RT_{pm} was about 51 – 81 %. At field site 1 the cumulative seepage water fluxes differed only up to 4 % between the different treatments. At field site 2 the varying rooting depth affected the total amount of cumulative drainage water only slightly. The ratios between the treatments were constant and the total amount of cumulative drainage water under RT_{pm} was about 15-16 % and 13-14% less compared to RT and CT, respectively. The runoff rates at field site 2 were constant as affected by variation of rooting depth.

Table 5
Sensitivity of cumulative water fluxes and water storage to changes in the spatial distribution of the root system after the simulation period of 86 days

Field site 1			RTpm					RT					CT		
Root	ΔW	T	E	S	R	ΔW	T	E	S	R	ΔW	T	E	S	R
depth	$l\,m^{-3}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-3}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-3}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$
10 cm	-9	116	43	1277	3	-9	123	86	1241	1	-12	140	62	1339	1
20 cm	-10	139	40	1197	4	-10	138	75	1176	1	-13	141	62	1321	2
30 cm	-9	141	41	1183	4	-9	140	67	1143	1	-13	140	64	1306	1
40 cm	-9	140	41	1182	4	-9	140	68	1146	1	-13	140	63	1299	2
50 cm	-9	139	42	1183	5	-9	139	68	1139	1	-13	139	63	1295	1
60 cm	-9	138	42	1186	4	-9	138	68	1139	1	-13	138	64	1302	1
mean	-9	135	42	1201	4	-9	136	72	1164	1	-13	140	63	1310	1
std.dev.	0	9.47	1.02	37.43	0.58	0.39	6.42	7.68	40.17	0.06	0.26	1.02	0.80	16.70	0.33

Field site 2			RTpm						RT						CT			
Root	ΔW	T	E	S	R	D	ΔW	T	E	S	R	D	ΔW	T	E	S	R	D
depth	$l\,m^{-3}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-3}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-3}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$	$l\,m^{-2}$
10 cm	-36	46	16	0	184	372	-37	45	33	8	120	441	-37	47	30	2	134	411
20 cm	-36	49	15	0	185	368	-37	47	31	8	120	437	-37	48	26	2	134	410
30 cm	-36	50	15	0	185	367	-37	48	29	8	120	434	-37	48	27	1	134	408
40 cm	-36	50	16	0	185	365	-37	48	28	8	120	433	-37	49	27	2	131	410
50 cm	-36	50	16	0	186	365	-37	49	29	8	120	431	-37	49	27	1	134	407
60 cm	-36	50	16	0	186	365	-37	49	29	8	120	432	-37	49	28	2	134	406
mean	-36	49	16	0	185	367	-37	48	30	8	120	435	-37	48	27	2	134	409
std.dev.	0.20	1.51	0.33	0.00	0.50	2.63	0.17	1.50	1.84	0.05	0.33	3.88	0.12	0.82	1.13	0.03	1.19	2.20

RT_{pm}: Ridge tillage with plastic mulch; RT: Ridge tillage without plastic mulch; CT: Conventional tillage with a flat surface, grey: original rooting depth used for model calibration; ΔW: change in water storage, T: Transpiration, E: Evaporation, S: Seepage, R: Runoff, D: Drainage; note that seepage is the only subsurface outflow of field site 1.

Table 6 shows the cumulative water fluxes after a simulation period of 86 days resulting from the percentage variation of the evapotranspiration (ET) rate. Generally the amounts of cumulative runoff at field site 1 and cumulative seepage at field site 2 were negligible. As we expected, the increase of the ET rate to 100% resulted in decreased cumulative seepage water fluxes at field site 1 and decreased runoff and drainage water fluxes at field site 2. As affected by the variation of ET rates the most sensitive component of the water balance was seepage water at field site 1. By reducing ET to 0%, cumulative seepage increased by 56 %, 65% and 61 % under RT_{pm}, RT and CT, respectively, whereas the increase of ET to 100% led to a decrease in seepage water up to 39% under RT_{pm} and CT and 41% under RT. By reducing ET to 0 %, cumulative drainage water at field site 2 increased between 14-15% under all treatments. In the case of increasing ET by 100 % the seepage water was reduced to

12-13% under all treatments. Significant runoff rates after a simulation period of 86 days occurred only at field site 2. The results revealed that cumulative runoff was not sensitive to the variation of ET rates. By reducing ET to 0% the maximum change in runoff was only 3 % under all treatments, whereas a 100% increase of ET led to a reduced runoff of 3% under RT_{pm} and RT and 6 % under CT. The ratio of the amounts of cumulative water fluxes between the different treatments was also not sensitive to the variation of ET at field site 2. The ratio of cumulative drainage and runoff rates at field site 2 differed only slightly to a maximum of 2 %. By increasing ET rates at field site 1, the ratio of seepage water fluxes under RT and RT_{pm} increased from 2 to 8 % and from 1 to 6% between RT and CT.

Table 6
Sensitivity of cumulative water fluxes and water storage on percentage change of evapotranspiration (ET) after a simulation period of 86 days

Field site 1			**RTpm**					**RT**					**CT**		
ET	ΔW	T	E	S	R	ΔW	T	E	S	R	ΔW	T	E	S	R
rates	$l\ m^{-3}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-3}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-3}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$
-100%	-3	0	0	1850	6	-2	0	0	1883	1	-3	0	0	2097	1
-80%	-3	28	10	1707	5	-3	28	21	1702	1	-4	28	21	1898	2
-60%	-4	56	21	1566	5	-5	56	40	1529	1	-5	56	39	1711	1
-40%	-6	84	30	1427	6	-6	84	52	1382	1	-7	84	50	1555	2
-20%	-7	113	37	1299	4	-9	112	61	1256	1	-10	112	56	1427	2
0	-9	141	41	1183	4	-12	140	67	1143	1	-13	140	64	1306	1
20% +	-12	169	44	1075	5	-16	169	74	1037	1	-16	169	69	1190	1
40% +	-15	196	47	975	3	-19	196	84	936	1	-18	197	75	1079	1
60% +	-18	223	51	882	3	-22	224	94	842	1	-21	223	80	978	1
80 % +	-21	248	53	797	3	-25	250	106	753	1	-24	249	89	884	1
100 % +	-23	271	56	721	5	-28	275	118	669	1	-27	272	102	799	1
mean	-11	139	35	1226	4	-13	139	65	1194	1	-13	139	59	1357	1
std.dev.	7.23	90.86	18.34	377.66	1.29	9.08	91.94	35.71	396.38	0.13	8.50	91.32	29.94	423.85	0.40

Field site 2			**RTpm**						**RT**						**CT**		
ET	ΔW	T	E	S	R	D	ΔW	T	E	S	R	D	ΔW	T	E	S	R	D
rates	$l\ m^{-3}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-3}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-3}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$	$l\ m^{-2}$
-100%	-35	0	0	0	190	421	-36	0	0	9	124	497	-23	0	0	1	138	485
-80%	-35	13	6	0	189	409	-36	12	11	8	123	483	-37	12	11	1	137	471
-60%	-36	22	9	0	188	398	-36	21	17	9	122	468	-37	21	17	1	136	457
-40%	-36	31	11	0	187	387	-37	30	22	8	122	456	-37	30	21	1	134	446
-20%	-36	41	14	0	186	377	-37	39	25	8	120	446	-37	39	24	1	135	434
0	-36	50	16	0	185	367	-37	48	29	8	120	435	-37	48	27	1	134	423
20% +	-36	59	17	0	184	357	-37	57	33	8	119	423	-37	58	30	1	134	412
40% +	-36	69	19	0	183	348	-37	66	37	8	119	412	-37	67	32	1	133	401
60% +	-36	78	20	0	182	339	-37	75	41	8	118	402	-38	76	34	1	132	390
80 % +	-36	87	21	0	181	329	-37	84	45	8	118	392	-38	85	39	1	132	380
100 % +	-36	97	22	0	180	320	-37	93	48	7	117	382	-38	94	44	1	126	373
mean	-36	50	14	0	185	368	-37	48	28	8	120	436	-36	48	25	1	134	425
std.dev.	0.25	31.51	6.96	0.00	3.29	33.14	0.38	30.41	14.81	0.45	2.29	37.51	4.24	30.61	12.64	0.08	3.20	37.30

RT_{pm}: Ridge tillage with plastic mulch; RT: Ridge tillage without plastic mulch; CT: Conventional tillage with a flat surface, grey: original ET rate, which was calculated based on FAO dual crop coefficient approach and used for model calibration; ΔW: change in water storage, T: Transpiration, E: Evaporation, S: Seepage, R: Runoff, D: Drainage; note that seepage is the only subsurface outflow of field site 1

4 Discussion

The modeling study showed that the simulation for field site 1 predicted the measured pressure heads reasonably well, whereas pressure head measurements at field site 2 were not well represented by the model simulation.

As the Hydrus 2/3D code does not calculate surface runoff directly, it was necessary to multiply the precipitation data by a factor of 2 for indirectly simulating runoff from plastic mulched ridges to the permeable furrows. This simplified method does not reflect the real field conditions, because ridges were often uneven and small depressions at the top of the ridges support the development of water storage in puddles. However, simulation results between observed and simulated pressure heads showed that the multiplication method was adequate to overcome the problem in calculating surface runoff. This was confirmed by Dusek et al. (2010), who also found that field conditions are better reflected by increased precipitation in comparison to the original data.

Additionally, the simulation neglected that interception on the crop canopy reduces the amount of infiltration water, which plays a relevant role especially during the main growing stage. Field observation showed that the potato canopy covered up to 80% of the surface area. Timlin (2001) confirmed the great influence of water redistribution, which can be caused by crop canopies and suggested to simulate canopy architecture and flow processes. Finally, root development during growing season could not be simulated and might result in an overestimated root water uptake at the beginning of the growing season. However, the sensitivity analysis revealed the low impact of different rooting depths on water balance components such as drainage, runoff and seepage. The calculation of evaporation and transpiration rates was based on the FAO dual crop coefficient approach by Allen (1998), which uses empirical crop coefficients. It is evident, that this procedure can only be an approximation of evaporation and transpiration rates, however, the sensitivity analysis of water balance components on percentage changes of evaporation and transpiration rates showed that cumulative seepage water flux was sensitive, while drainage and runoff rates were relatively robust. The ratio of cumulative seepage, drainage and runoff water fluxes between the different treatments was also robust to changes in root depth and evaporation and transpiration rates.

During dry periods pressure head gradients were found to deviate horizontally in the case of RT_{pm} indicating a lateral flow direction from the furrows to the ridges in the top layer. These patterns were weakened under RT as only the topography affected soil moisture pattern. Pressure head gradients under RT deviated more vertically, which forced water to flow in a more enhanced vertical than lateral direction. Under conventional tillage (CT), pressure head gradients were found to be exactly vertical to the soil surface inducing a clearly vertical soil water movement. During monsoon events, however, the dominating flow directions were not as pronounced as during dry conditions. At field site 1, where the top layer was characterized by a coarse sandy loam, ridges were fully saturated in the root zone, even in the case of RT_{pm}. At field site 2, the root zone was protected against full saturation in the case of RT_{pm} because of a less coarse textured top layer and a lower hydraulic conductivity. While drainage in the root zone accelerated, when the topsoil consisted of a coarser-textured material and full saturation occurred only for short after the rain event, the less coarse-textured topsoil was close to full saturation for a much longer time period. However, it has to be considered that monsoon events in the measurement period 2010 were indeed comparatively small with a maximum daily precipitation amount of <80 mm and a relatively low intensity. Precipitation observations of former years indicated that monsoonal events can reach up to 100-150 mm d^{-1}. Taking even higher precipitation amounts into account, even a finer textured top layer would be fully saturated. Hence, the application of sandy soils with a coarse texture, which equals the local method, ensures a rapid drainage of the root zone.

The analysis of flow velocities during monsoon events showed that an interflow phenomenon occurs, when the topsoil is characterized by a coarse soil texture, a high saturated hydraulic conductivity and additionally overlies finer textured subsoil with an underlying compact bedrock material. These conditions are enhanced by ploughing and application of sandy soil material before growing season. Based on these soil properties, flow velocities in the topsoil were simulated to be 6 to 8 times higher than in the overlying ridge and in the underlying subsoil. Therefore the high flow velocities in the topsoil assure a quick drainage of the root zone particularly at sloped field sites but concurrently might increase the risk of leaching via interflow. In contrast, the soil properties differed at field site 2 and interflow was not evident in the simulation. A generally finer soil texture in the top layer slows down the drainage process in the root zone but decreases the risk of leaching via interflow.

The comparison of drainage water under different management strategies showed that plastic mulching reduces the amount of drainage water up to 16% and consequently reduces the contribution to the groundwater. Accordingly, plastic coverage might reduce the conservative transport of nitrate to groundwater and might temporally extend the nitrate availability in the root zone below the plastic coverage, but further research on leakage of fertilizer and agrochemicals under plastic mulched ridge cultivation is necessary. Concurrently, the modeling study showed that RT_{pm} increases surface runoff up to 65% compared to RT and CT, which supports a quick water contribution to the river network in the catchment. A substantially increased runoff generation in a plastic mulched pineapple culture was also found by Wan and El-Swaify (1999). The high impact of plastic mulched ridge cultivation in agricultural fields on hillslopes by increasing significantly surface runoff, exacerbate the problem of phosphorous transportation with sediments via overland flow to the stream networks. This is supported by Kim et al. (2001), who found that the discharge of phosphorous associated with sediments from agricultural areas cause eutrophication and deterioration of water quality in downstream reservoirs in South Korea.

5 Conclusion

In this study, a combination of field measurements and process-based model simulations was used to evaluate the effect of plastic mulched ridge cultivation in comparison to ridge cultivation without plastic coverage and conventional flat tillage management on soil water dynamics. It was demonstrated that plastic mulching induces typical soil moisture patterns mainly in the topsoil during dry periods compared to the other tillage systems, whereas the impact of tillage management on soil water dynamics in the subsoil was low. During monsoon events, however, no significant soil moisture patterns caused by tillage management could be detected since the soil profile was almost fully saturated, depending on the soil texture.

Summarizing the advantages and disadvantages of the three different management systems on hillslopes in a monsoon climate, conventional tillage (CT) is inadvisable due to the higher amounts of seepage water and the higher rates of surface runoff compared to RT. In addition, a flat surface is predestined for erosive denudation. RT_{pm} was found to have the lowest amount of drainage water and the highest runoff rates. Ridge tillage without coverage (RT) showed higher amounts of drainage water compared to RT_{pm} as well as the lowest runoff rates of all management practices. Therefore, ridge tillage without coverage (RT) was evaluated as the best management strategy to avoid high amounts of surface runoff. In order to reduce drainage water amounts, however, ridge tillage with plastic mulch (RTpm) showed the best results. Additionally, it has the advantages of earlier plant emergence and weed control as reported by local farmers. To combine the advantages of both treatments as well as to diminish the negative effects of both, we conclude that the application of perforated and biodegradable plastic mulch seems to be the most promising method in agricultural dryland farming affected by monsoonal climate.

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Chapter 5 Ridge and furrow cultivation: challenges for analysis of water fluxes and nutrient leaching

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Abstract

Ridge and furrow (R/F) cultivation is historically one of the oldest modifications of the soil surface for efficient use of water, soil, nutrients, and heat by agricultural crops. All over the world, there is a remarkable variety in R/F systems, each of which is specifically adjusted to the priority objective. Despite the worldwide spread and importance of this cultivation system, there is no clear systematization of R/F cultivations and evaluation of changes of fluxes of water and nutrients compared to cultivation on flat soil surface. Here, we provide a comprehensive systematization of R/F cultivation depending on their main aims, allocation of crops and agrochemicals (fertilizers and pesticides), and addition of irrigation water. We analyzed the most common land use systems with R/F cultivation and evaluated their main advantages and shortcomings. Based on the literature review we suggested some approaches to decrease the shortcomings and to optimize water and nutrient use efficiency. The most important difference of R/F cultivation compared to the flat surface land use systems is the complete change of water infiltration and water fluxes in soils and associated leaching of dissolved nutrients. This is especially pronounced in humid climates and climates with uneven annual distribution of precipitation (monsoon or Mediterranean climates). Redistribution of water fluxes from ridges to furrows is a great challenge for their measuring in field, analysis, modelling, and upscaling. Because of the increased water infiltration in furrows, but allocation of the crops on the ridges, the potential of leaching is thought to increase up to 6 times compared to flat cultivation systems. Experimental results on water and nutrients leaching in R/F cultivation as well as modelling studies considering the specifics of R/F cultivation are extremely scarce. In the last 30 years, the R/F cultivation systems were adopted for a wide range of different crops and research on various aspects of R/F cultivation has continuously increased. As the interest is expected to further increase in future, we call to focus future studies on redistribution of crop growth limiting factors and water by ridges and furrows and to develop models considering specifics of this modification of the soil surface.

Keywords: Nutrient cycles; ridge and furrow practice; water and heat management; R/F cultivation; ridge tillage; ridge-till

1 Introduction

The ridge and furrow cultivation (R/F cultivation) is an ancient agricultural practice. The system was developed independently in South and Central America (Turner and Harrison, 1981), in Africa (Pereira et al., 1967), and in Asia (Chandler, 1981; Janick, 2002). The origins can be traced back to the arid and semi-arid tropics, which are characterized by soils with shallow depths and of low fertility as well as by low precipitation (Lal, 1991). In these arid and semi-arid regions, the ridges of the R/F cultivation enlarged the room for the growth of crops roots and concurrently provided a better water supply for the plants. The creation of ridges and furrows enabled the irrigation of the plants by accumulating water in the furrow zones. In humid regions, however, the ridges were used for draining surplus water out of the root zone (Hatfield et al., 1998).

Today, modern R/F cultivation is a cultural practice widely used throughout the world with many different alterations but with the ridges as a planting zone as a common modification. Row crops such as maize *(Zea mays* L.), sunflower (*Helianthus annuus*), sugarcane (*Saccharum* L.), soybean *(Glycine max* (L.) Merr.), sorghum (*Sorghum bicolor* (L.) Moench), and cotton (*Gossypium hirsutum* L.) are cultivated on ridges. Further, root crops that would be damaged by inundation are commonly cultivated in R/F systems. Finally, crops such as potatoes (*Solanum tuberosum*)) and asparagus (*Asparagus officinalis* L.) are cultivated on ridges to ease the harvesting. Reasons for adopting R/F cultivation are manifold and include reducing costs, enhancing soil fertility and rooting depth, improved soil temperature and moisture in spring, reducing contamination of water supplies and soil erosion, facilitating multiple cropping, and improving pest management (Borges and Mallarino, 1999; Hatfield et al., 1998; Shi et al., 2012). R/F cultivation is not as common as other agricultural practices but has become an established crop production practice that is widely employed for some of the world's staple foods (Klein et al., 1996).

1.1 Worldwide use of R/F cultivation

In North America, R/F cultivation is an important component or sub-system of conservation tillage systems since the early 1980s (Lal 1991; Stone et al. 1990) and gained widespread use in the Midwest, especially in the Corn Belt, as the interest in limiting soil erosion and leaching of agrochemicals as well as promoting water conservation increased during the past decades (Al-Kaisi et al., 2005). Commonly, the permanent ridges are cultivated for several years with a corn-soybean rotation (Al-Kaisi et al., 2005; FAO, 1993). In California, however, sugarbeet (*Beta vulgaris* L.) is cultivated on ridges to facilitate furrow irrigation (Krause et al., 2008). In many dryland areas of Africa, ridges with additional cross-ties in the furrows at short intervals are traditionally used for sweet potato (*Ipomoea batatas* (L.) Lam.) production, but were modified through research to be used for grain crops such as sorghum and maize (Araya and Stroosnijder 2010; Shaxson and Barber 2003). The usefulness in water conservation of this cultural tradition has been experimentally demonstrated in eastern Africa (Araya and Stroosnijder, 2010; Honisch, 1974; Pereira et al., 1967), and in western Africa (Hulugalle, 1990; Lal 1991). In Europe, R/F cultivation is mostly used for the cultivation of potatoes, asparagus, and carrots (*Daucus carota* L.) to ease the harvesting rather than for soil conservation. The destructive harvest allows only for a temporary use of the ridges. Other crops under ridge cultivation are strawberries. In most parts of Europe, however, R/F cultivation for other crops has only been studied in experiments (Louwagie et al., 2009). Ridge tillage in Asia is predominantly common in the temperate regions to extend the cultivation period of vegetables and to allow an early planting in the spring. In South Korea, plastic covered R/F cultivation is extensively used for the production of dry crops such as potatoes, radish (*Raphanus sativus* L.), bean (*Glycine max* (L.) Merr), cabbage (*Brassica rapa*), and pepper (*Capsicum annuum*) (Kettering unpublished; Kwon et al., 2006). Plastic covered ridges for planting with bare furrows as an infiltration zone are also the conventional planting pattern for potatoes in the semi-arid regions of northwestern China (Tian et al., 2003). In the flat, lowland areas of Northeast China, R/F cultivation has additionally been adapted to ridge and furrow rainwater-harvesting (RFRH) systems to improve water availability and water use efficiency (WUE), and to increase crop production (Gosar and Baričevič, 2011; He et al., 2010; Tian et al., 2003).

Based on the literature review we conclude that the R/F cultivation is used all over the world for a very broad range of agricultural crops. To our knowledge, however, there were no comprehensive systematizations of R/F cultivation and, even more important, the changes of water and nutrient fluxes were not yet described. Therefore, we focused this review on the alterations of water and nutrient fluxes induced by the R/F cultivations and subsequent challenges for their analysis, modeling and upscaling.

2 Systematization of R/F cultivation

R/F cultivations can be divided into two main types: Cultivation of crops on the ridges and cultivation of crops in the furrows. While the cultivation of crops on ridges is an ancient practice, which gained again importance in the recent decades as part of the conservational tillage systems for intensive agriculture, cultivation in furrows with micro-catchment rainwater harvesting is a modification, especially for subsistence agriculture in arid and semi-arid regions without additional irrigation. In spite of their substantial differences, both types try to manage and optimize water fluxes and infiltration with the aim to achieve favorable conditions for plant growth. This review is mainly focused on R/F cultivation systems, in which crops are cultivated on ridges. To draw a complete picture of R/F cultivation systems, both types will be shortly introduced. However, it was not the aim of this review to present and to describe mechanic approaches to produce and to maintain the ridges and the furrows and we therefore refer to the cited studies in each chapter for further details to this topic.

2.1 Cultivation in furrows

Ridge and furrow rainwater harvesting (RFRH) was investigated in the flat, lowland, semi-arid conditions of northwest China (Gosar and Baričevič, 2011). The main advantage of this system is the protection of crops against water scarcity in arid and semi-arid regions with limited and sporadic precipitation or in regions, where irrigation water is not available or too costly (Li et al., 2000). RFRH systems consist of an often plastic covered runoff area (ridge), which serves as the rainwater harvesting zone and an adjacent bare or mulched basin area (furrow), which serves as the infiltration zone as well as the planting zone. Crops are planted on both sides of the furrow. The objective of rainwater harvesting is to induce runoff on the ridges, collect and store the water in the furrow zone, and conserve it in the root zone (Hendrickx and Flury, 2001). If water is scarce, the plants in the furrow benefit from the additional water, and concurrently the soil water conservation and the WUE may be improved compared to the flat cultivation systems (Tian et al., 2003). Measured runoff efficiency (runoff/rainfall) of plastic-covered ridges averaged to 87% as compared to 7% for bare ridges (Li et al., 2000). Besides the improved water availability to plants, the system may also improve yields, production stability, and soil temperatures (Gosar and Baričevič, 2011; Xiaolong et al., 2008). The major advantages are that it is simple, cheap, replicable, efficient and adaptable (Li et al., 2000). The system is mainly used for growing medium water demanding crops, such as maize, sorghum, groundnuts and millet (Hatibu and Mahoo, 1999). RFRH systems are also widely used for corn production in northwest China (Li et al., 2000).

2.2 Cultivation on ridges

Cultivation on ridges is an ancient agricultural practice used for a variety of crops and for a variety of reasons. Hence, there exist numerous subtypes, each of which is specifically adjusted to the priority objective (Krause et al., 2008). The basic system of cultivation on ridges consists of a bare elevated ridge, which serves as the planting zone and a furrow, which serves as the infiltration zone. The main objectives of the ridge planting are to improve the plant root environment and to protect the crops against anoxic conditions due to water logging during wet periods or during heavy rainfall (Benjamin et al., 1990; Leistra and Boesten, 2010a). The ridges improve the soil environment for seed germination, early crop emergence and growth, because of warmer soil temperatures in cool and/or wet spring climates and by favorable soil physical characteristics (Krause et al., 2008). The warming combined with the better drainage and aeration of both poorly-drained and moderately well-drained soils (Hatfield et al., 1998) allows the ridges to dry out sooner than flat soils. As the ridges warm up and dry out sooner in spring, they promote early planting and extend the growing season (Jaynes and Swan, 1999; Leistra and Boesten, 2010a). Using the furrows as driving paths, the ridges maintain their loose structure during growing season and show less compaction, leading to a more favorable surface soil structure in the topsoil (Leistra and Boesten, 2010a). In the case of potato, they create room for the growth of tuber and also facilitate mechanical harvest (Harms and Konschuh, 2008). This system is typically used for the production of potatoes in the USA, in Europe and in various other parts of the world. R/F cultivation is also common in the Corn Belt of the USA for the cultivation of corn and soybean. The following chapters refer mainly to this type of R/F cultivation.

3 Specifications of cultivation on ridges

Crop cultivation on ridges varies with respect to several factors such as the residence time of the ridges and their shape, width and height. This chapter describes some of the most important differences and modifications of the above described R/F cultivation type (Table 1).

Table 1 R/F cultivation: main types, aims, specifications, and occurrence

	Cultivation			
	on ridges			**in furrows**
Climate	Humid	Semiarid-arid, no irrigation	Semiarid-arid, with irrigation	Semiarid-arid
Main aims	Improve root environment; Improve soil physical properties; Protection against water logging; Extend growing season; Ease of the harvesting	Rainwater harvesting; Better water management; Enlarged soil volume for root growth	Improve plant root environment; Improve soil physical properties; Protection against water logging; Extend growing season; Ease of the harvesting	Rainwater harvesting; Better water management; Production stability
Common crops	Potato, asparagus, sugarbeet, carrots, radish, strawberries, cabbage, soybean, maize	Maize, sorghum, sweet potato, groundnuts, millet, potato	Maize, soybean, sorghum, wheat, potato, sweet potato, cotton, sugarbeet	Maize, sorghum, groundnuts, millet, cotton
Main cultivation area	South Korea, Germany, USA, China, Canada	Africa, China	USA, China	China, Africa
Irrigation	No irrigation; Furrow irrigation; Sprinkler irrigation; Drip irrigation	No irrigation	Furrow irrigation; Sprinkler irrigation; Drip irrigation	No irrigation
Ridge modification	PE mulch on ridges	-	-	PE mulch on ridges
Residence time of ridge	Temporary (one vegetation period)	Semi-permanent, permanent	Permanent	Semi-permanent
Furrow modification	Mulch, PE mulch, plant residues	Cross-ties/dyked furrows	Plant residues	PE mulch, gravel mulch

3.1 Residence time of ridges

The residence time of ridges and furrows is an important factor for the characterization of the R/F cultivation and the respective management because it varies from temporary ridges usually used for one vegetation period up to permanent ridges usually used for several years up to a decade. Permanent ridges, which are maintained for several years of crop production, are typically used for corn-soybean rotations in the Corn Belt of the USA (Al-Kaisi et al., 2005) as well as in Ontario (Stone et al., 1990).

The initial ridges are usually built when the cultivated crop is corn or sorghum. The following crop is planted on the ridges formed during the cultivation of the previous crop. Permanent ridge cultivation follows a sequence of defined operations performed throughout the course of a year (Hatfield et al., 1998). In principle, there are no soil tillage operations between the harvest and the planting of the annual crops. The fields are usually undisturbed until the next spring to trap snow and reduce water runoff and erosion (Klein et al., 1996). At sowing, the plant residues of the previous crop together with the top soil of the ridges are shifted from the ridges to the furrows. This shifting leads to the protection of the furrow soil from direct rainfall and erosion (Jaynes and Swan, 1999), to a faster warming and drying of the bare ridge (Hatfield et al., 1998) as well as to the removal of weed seeds from the ridges (Burton et al., 2006). The seed is then planted into the center of the preserved ridges. The preservation of the ridges and the planting of the crop in the same location every year utilize a controlled wheel traffic pattern with trafficked furrows, non-trafficked furrows, and cultivated ridges (Waddell and Weil, 2006). Ridges with a height of approximately 10 cm increase the surface area by approximately 10% compared with flat tillage systems (Stone et al., 1990). Permanent ridges are usually used with furrow irrigation, with which it works well.

Temporary ridges are typically used in cool and wet climates, where the growing season is short. In China, South Korea and Japan, the ridges are after their formation in spring often covered with black PE mulch to extend the short growing season and allow an early planting (Kettering unpublished; Kwon et al., 2006). The black PE mulch raises the soil temperatures, promotes the faster warming and drying of the ridges, and suppresses the weed growth. In South Korea's vegetable cultivation, the plant residues of the previous year's crop are usually mixed into the soil by plowing before ridging. After fertilization, the field is plowed again and ridges and furrows are formed. With the ridging of the field, the biggest portion of the fertilizer is shifted into the ridges and consequently allocated in the root growth zone (Kettering unpublished). The ridges are then covered with black PE mulch using a hand operated tool. The furrow is usually kept bare and herbicides are applied only in the furrow zone. The plastic mulch in combination with bare furrows accelerates the surface runoff from the ridges into the furrows and concurrently might increase the soil erosion especially at fields on slopes (Rice et al., 2001). The seed is placed in the planting holes at the top of the ridges. After harvesting, the PE mulch is either removed from the ridges and the field is plowed or the PE mulch is left until next year's spring and removed then before plowing. Recently, experiments were carried out on cotton fields in the semi-arid climate of Turkey to evaluate effects of temporary ridges formed in autumn before planting and of ridges formed about a month before planting (Gürsoy et al., 2011). The former resulted in highest emergence, earliest maturity and greatest seed cotton yield. Additionally, temporary ridges are used to facilitate mechanical harvest, as in the case of potato or asparagus. Growing of crops on ridges also facilitates furrow irrigation.

3.2 Ridge and furrow modifications

The use of mulches, especially plastic mulches, is a common modification of the ridges in vegetable production systems (Rice et al., 2001). Plastic mulches applied to the ridges cover the entire soil around the stem of a plant from all sides. The effects of the PE mulches depend on the material characteristics and the color (Lamont, 1993; Lamont, 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 (Lamont, 1993; Lamont, 2005; Moreno and Moreno, 2008). Advantages and disadvantages of plastic mulches were referenced in detail by Lamont (1993). The main advantages of black PE mulch are that the ridges warm up earlier in spring, promote earlier-maturing of the crops, enhance plant growth, and lead to earlier yields. Because of the reduced evaporation, soil moisture is conserved and irrigation requirements may decrease. The plastic mulch additionally functions as weed control by suppressing weeds due to reduced light penetration into the soil. It prevents soil compaction and concurrently increases root branching and extension. The impervious plastic mulch also sheds excess water off the ridges and protects the plants against decay due to water logging. It is also suggested that the impervious PE mulch protects the fertilizer located in the ridges by diverting water from the ridge to the furrow and therefore may reduce fertilizer leaching (Dusek et al., 2010; Lamont, 1993). Plastic mulching in vegetable production is often used in combination with other components such as drip irrigation or fertigation to achieve maximum efficiency (Lamont, 1993). However, the massive use of these PE materials poses an environmental risk as its removal and disposal from the fields after harvesting are major problems (Lamont, 1993; Moreno and Moreno, 2008). Therefore, we recommend photodegradable and biodegradable plastic mulches.

Use of mulching is also a common modification of the furrows. In some R/F cultivation systems the furrows are temporary covered with plant residues from the previous year’s crop to protect the furrow soil from direct rainfall and erosion (Jaynes and Swan, 1999). However, the acceptance of this practice as conservation tillage can fit only for permanent R/F cultivations, which leave more than 30% of the fields covered with plant residues (Stone et al., 1990). The temporary R/F cultivation with their renewed ridges every year cannot be accepted as conservation tillage. In South Korea e.g., the furrows are mostly kept bare after planting as well as during the entire growing season and the plant residues are mixed into the soil by plowing after the harvest (Kettering, unpublished). In drylands with erratic and unpredictable rainfall and where irrigation is either too costly or not available, furrows are modified to avoid or reduce water shortage and water stress for the plants. In these systems, cross-ties are constructed along the furrows to develop a series of small basins for trapping rainwater and runoff (Lal, 1991). This modification of furrows with cross-ties is in some parts of the world called dyked furrows. The system is amongst other used for the potato cultivation in Israel (Agassi and Levy, 1993) and in the drylands of Africa (Ibraimo and Munguambe, 2007).The cross-ties, which show in general a height of $^{1}/_{2}$ to $^{2}/_{3}$ of the height of the ridges, are set at intervals of 1 to 4 meters (Hulugalle, 1990). In Africa, they are usually used for a period of 6 seasons depending on the crop rotations (Ibraimo and Munguambe, 2007), while the dyked furrows for the potato production in Israel are only used for one season (Agassi and Levy, 1993). Tied ridging reduced water runoff as well as soil erosion and increased the soil water content in the root zone, the yield and the rainwater use efficiency (Araya and Stroosnijder, 2010). However, their efficiency depends largely on soil, slope, rainfall and ridge design characteristics (Ibraimo and Munguambe, 2007).

Finally, cultivation on ridges in different countries or of different crops is modified with respect to shape, width and height of the ridges or the furrows. It was found that ridge shape has an important effect on soil moisture, soil water distribution and redistribution, radiation absorption, organic carbon production, decomposition, and crop growth (Chen et al., 2011; Louwagie et al., 2009). Soil moisture or water use efficiency can be effectively influenced by ridges e.g. with a wider profile or a flattened top, which prolongs the time of the water to infiltrate into the ridge before being diverted into the furrow zones (Harms and Konschuh, 2008). Additionally, the ridge height has an influence on water and heat movement. The optimum height for the fastest warming up and drying of the ridges was defined at approximately 20 cm (Harms and Konschuh, 2008). For water and N distribution, Chen et al. (2011) found the optimum ridge width within the range of 60 to 75 cm for ridge-tilled systems in Northwest China. The dimensions of the furrows, however, depend largely on the water situation and on whether the furrows serve as irrigation/drainage channel, walking space, or as cultivation area (Kleinhenz et al., 1996).

3.3 Use of irrigation systems

Water infiltration in fields with R/F cultivation is complicated by the variability in amount, intensity, duration, and frequency of natural rainfall events and the type of vegetation (Chen et al., 2011).

Rainfed cultivation on ridges under sufficient natural rainfall is conducted in cool and humid regions such as South Korea and Japan (Kettering, unpublished). Rainfed cultivation on ridges in arid to semi-arid regions is widely used as rainwater harvesting technique in Africa (Ibraimo and Munguambe, 2007). However, most of the R/F cultivation systems rely on the additional use of irrigation. The dominating forms of irrigation are furrow irrigation systems, which work well with R/F cultivation, as well as sprinkler irrigation systems, which are similar to natural rainfall.

Using sprinkler irrigation, the irrigation water is pumped through a pipe system and then uniformly sprayed onto the crops through rotating sprinkler heads. It is suitable for most row and field crops (Brouwer et al., 1988). Because of a better control of irrigation timing, intensity and uniformity, sprinkler irrigation is generally thought to be more efficient than furrow irrigation (Butters et al., 2000; Saffigna et al., 1976). However, while the water is applied uniformly, the irrigation of the sprinkler water may be uneven due to the complexity of microtopography of the R/F cultivation, due to wind, plants and water pressure and might lead to non-uniform wetting patterns of the soil (Cooley et al., 2007; Smelt et al., 1981; Steiner et al., 1983). Microtopography, namely the slope of the ridge, leads to surface runoff of water from the ridges to the furrows. Additionally, stemflow was found to considerably alter the distribution of water entering the soil. Studies, which measured direct stemflow, found that 20 to 64% of the irrigation (Lamm and Manges, 2000; Saffigna et al., 1976; Steiner et al., 1983) and 4 to 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, its development, and weather conditions (Leistra and Boesten, 2008). While it increases with crop development, it decreases with its senescence (Dolan et al., 2001; Quinn and Laflen, 1983). Increasing wind speed, however, is assumed to decrease stemflow (Leistra and Boesten, 2008). Sprinkler irrigation is also assumed to be not suitable for soils, which easily form a crust: loamy and clay soils. However, also sandy soils were found to become hydrophobic under sprinkler irrigation. This led to even more shedding of water into the furrows with further infiltration (Cooley et al., 2007; Robinson, 1999).

Furrow irrigation is used in many arid, semiarid, and sub-humid regions for the irrigation of row crops or crops that would be damaged if water covered their stems (Brouwer et al., 1988). The main reasons for applying furrow irrigation it that it is cheap and simple to install and operate (Benjamin et al., 1998; Butters et al., 2000). Additional benefits are the reduced risk of leaf diseases because irrigation water does not wet the foliage, the possible adaption to a wide range of soil types and topography, and that wind has no effect on application efficiency (James, 2004). Water is usually applied to each furrow in the field by gravity without the need for power. WUE is relatively low, ranging from 35 to 60%, due to percolation losses in the furrows. Additionally, overirrigation near the source is possible to occur in the need to apply sufficient water to replenish the root zone of the soil farthest from the source (Benjamin et al., 1998; Butters et al., 2000 Stevens et al., 2007).

As mentioned above, the irrigation water is usually applied to each furrow but due to the high leaching losses, the low WUE and the high irrigation requirements of this method some studies have proposed irrigating alternate furrows instead (Benjamin et al., 1998; Butters et al., 2000). Irrigation water use was decreased by 30 to 50% using alternate-furrow irrigation, which in turn led to less water percolation and fertilizer leaching (Benjamin et al., 1998). Additionally, some studies conducted research on R/F cultivation in combination with drip irrigation to increase WUE and to reduce irrigation requirements and leaching of agrochemicals (Cooley et al., 2007; Waddell et al., 2000). Drip irrigation involves frequent applications of irrigation water and/or fertilizer only in the parts of the soil where the roots grow, unlike sprinkler and furrow irrigation, where the whole soil profile is wetted. Only 30% of the volume of soil may be wetted by drip irrigation (Brouwer et al., 1988; Waddell et al., 2000). Research on reduced water use by drip irrigation compared to other irrigation methods shows a wide range of results. It was found that drip irrigation could reduce water use by 8 to 50% compared to sprinkler irrigation (Shalhevet et al., 1983; Waddell et al., 1999) and by 26 to 57% compared to furrow irrigation (Hanson et al., 1997). It was also suggested that the uniformity of water distribution was higher in drip irrigation when compared to other irrigation methods (Cooley et al., 2007).

3.4 Placement of fertilizers

Fertilizers (NPK) are usually applied broadcast and uniformly before planting or placed within the ridge during planting. Application methods depend largely on the fertilizer form as well as on the technical equipment available. Anhydrous ammonia may be knifed into the ridges. Granular or liquid fertilizer may be side dressed during the first cultivation (Stone et al., 1990). However, when fertilizer is applied broadcast to a flat field, ridging will drastically change the distribution of the broadcast granules and result in accumulation of the biggest portion of fertilizer in the ridges (Smelt et al, 1981). This increases the allocation of the fertilizers within the rooting zone (for the crop cultivation on ridges) and consequently increases the fertilizer use efficiency as well as decreases its unproductive losses. Placement of agrochemicals plays an important role for their uptake efficiency and in reducing their leaching. Several studies suggested that isolation of the chemical from the percolating water by placing the agrochemical on or near ridge tops may reduce the leaching due to microtopography (Clay et al., 1992; Hamlett et al., 1990; Kemper et al., 1975) and may increase uptake by plants (Blaylock and Cruse, 1992). During rainfall or irrigation, water is assumed to concentrate in the furrow where it would not come in contact with the chemical localized in the ridge at a level equal to or higher than the water level in the furrow.

4 Repercussion of R/F cultivation: Redistribution of water

The R/F cultivation affects physical, chemical and biological soil properties, which differ between ridges and furrows. The main soil physical changes are compaction, aeration, aggregate size, volumetric soil water content, water content at field capacity, water content at wilting point, mean saturated hydraulic conductivity (Bargar et al., 1999; Cooley et al., 2007; Liebig et al., 1993), and penetration resistance (Laszlo et al., 2004). The main soil chemical changes are organic carbon (C) and total N amounts (Hatfield et al., 1998). The main biological changes are microbial biomass C and N contents as well as inorganic N contents (Müller et al., 2009). However, the redistribution of water and the modification of water circulation within the soil is the most fundamental alteration of the R/F cultivation.

The studies of water fluxes in R/F cultivations are focused on 1) the redistribution of water on the soil surface from ridges to furrows and 2) on the subsequent migration of water within the soil under ridges and furrows. Several studies proved experimentally that infiltration and initial water movement occurred largely in the furrows mainly due to surface runoff. Stemflow and water repellence have also been recognized to cause additional non-uniform infiltration in soils (Table 2). Bargar et al. (1999) concluded that infiltration and initial water movement in uncropped fields under natural rain occurred primarily in furrows. This was indicated by a more rapid increase in soil water content for furrow than for equivalent ridge positions at soil depths < 45 cm. The difference in water movement was reasoned with the surface runoff of a big fraction of the rain running from the ridges to the furrows and with less evaporation occurring in the furrows due to its plant residue cover. Same observations were made for an uncropped field assessed under furrow irrigations at soil depths < 30 cm (Chen et al., 2011). Surface runoff from the ridges to the furrows, when rainfall exceeded infiltration capacity, was also observed by visual ponding and measured water contents in an uncropped temporary R/F cultivation by Hamlett et al., (1990). This study compared three rainfall amounts, with the result that higher rainfall led concurrently to higher surface runoff into the furrows and deeper penetration in the furrow zone. Clay et al. (1992) also observed ponding of water in the furrows after a rainfall simulation in an uncropped field with established ridges. Leistra and Boesten (2008, 2010) suggested that around 20% of the applied irrigation water to a potato field surface-flowed from the ridges into the furrows within the first month of the experiment. Li et al. (2000), however, compared runoff from bare ridges to runoff from plastic mulched ridges. Runoff from plastic covered ridges showed an average runoff efficiency (runoff/rainfall) of 87%, with the maximum efficiency being close to 100%, while the runoff efficiency of the bare ridges with only 7% was considerably lower. Additionally, bare ridges produced only runoff under high intensity of the rainfall events, whereas the plastic mulched ridges were able to generate runoff also under low intensity of the rainfall. All above described studies were conducted in uncropped fields or at a time when the plant had not emerged yet and therefore represent the period between planting and the time at which crop start to considerably affect water infiltration and soil water movement. Waddell and Weil (1996, 2006) found under a fully developed corn canopy that stemflow funneled rain towards the ridge top, which led to a higher infiltration of water into the cropped ridges and to a large offset of surface runoff from the ridges to the furrows. In contrast, after harvest the surface flow from the ridges to the furrows was the dominant process. Cooley et al. (2007) found considerable stemflow under potato cultivation in the early part of the growing season, which decreased with the progressing growing season. They also observed that the soil had become hydrophobic under the sprinkler irrigation and this additionally promoted the surface runoff from the ridges to the furrows due to geometry. A development of water repellent soil in potato fields due to intensive cultivation and practice of reworking crop foliage back into the soil was also found by Robinson (1999). He observed that the irrigation only wetted the upper few centimeter of the ridges before flowing along the water repellent soil layers of the ridges into the furrows. Hence, the water repellent soil layer amplified the surface runoff from the ridges to the furrows occurring due to ridge slope. Additionally, crop emergence and further growth was found to exacerbate the shedding of water into the furrows due to interception and stemflow.

The subsequent movement of the infiltrating water in the soil was also often investigated (Table 2). Chen et al. (2011) and Bargar et al. (1999) indicated that the main infiltration and downward water movement occurred in the furrows, but was followed by delayed lateral and radial movements to the uncropped ridge positions. Bargar et al. (1999) suggested that the downward movement of water in the furrows might have been enhanced by macropore flow under untracked furrows, while the downward movement of water in tracked furrows was found to be slower. Chen et al. (2011) additionally measured that the wetting of the ridge tops took several minutes to hours after irrigation and was related to water potential gradient and unsaturated hydraulic conductivity. However, as both studies state that the vertical water movement under furrows was the main water flow direction, they found a reduced downward movement under the ridges. This was reasoned with the multiple roles of gravitational potential gradient, pressure gradient and the potential role of soil suction gradient. Chen et al. (2011) additionally measured soil water contents under three ridge widths and found that it had a significant effect on soil water distribution and redistribution in uncropped ridges. Ridges with more than 75 cm width were found to reduce lateral flow from the furrows to the ridges and created thereby a dry center in the ridge. Lateral flow from the furrows to the ridges was also measured by Waddell and Weil (2006) for cropped ridges. Midway between corn planting and harvesting, a negative hydraulic gradient was observed that indicated upward water movement from the furrows to the ridge tops. Additionally, they suggested that an argillic soil horizon found at the study site might have limited the downward flow of the water and consequently could have enhanced the lateral flow. In contrast, Hamlett et al. (1990), Starr et al. (2005) and Kung (1990) found only little or no indication of a lateral flow directed from the furrows to the ridges in uncropped ridges and potato ridges, respectively. While Chen et al. (2011) found that the ridges were wetted within minutes to hours after furrow irrigation, Cooley et al. (2007) measured that sprinkler irrigation resulted in a dry zone in the center of the ridges. The development of this dry zone was especially pronounced with the progress of the growing season and resulted in no response of the ridge centers to irrigation under well-developed crops. The excessive uptake of soil water by roots in the ridges, the hydrophobic soil layer of the ridges, which prevents infiltration into the ridges, the geometry of the ridges, which induced surface runoff into the furrows, and the decreasing stemflow during growing season were suggested to explain this dry zone development. Cooley et al. (2007) additionally compared sprinkler irrigation to drip irrigation and found that the latter was more efficient in supplying water to the center of the ridges in R/F cultivation. Robinson (1999) measured decreasing water contents in the ridges starting with the crop emergence and exacerbating with crop growth. They observed no or only little wetting effects in the ridge centers after the irrigation or a rain event. In their field observations, they found that after different rain events the ridge centers were visibly dry. This led to a distinct soil water deficit during the crop growth. Starr et al. (2005) also found that sprinkler irrigation did not reach the center of the ridges, even at comparatively high precipitation rates.

We conclude that the water movement by R/F cultivation consists on the following steps: 1) surface or nearly surface gravitational redistribution of rain or sprinkler water, 2) mainly vertical movement of water in the furrows by gravitation, and

3) redistribution of soil water within the soil mainly by capillary force. The water flux directed in the horizontal direction is a major challenge for the modelling approaches. In conventional modelling approaches it is more or less accepted that the water and nutrient flow is directed in a vertical direction. The water migrates downward after precipitation and shows an ascending flux if the soil surface is drying and plants use water for transpiration.

5 Redistribution of water and its implications for solute leaching

The most important difference of R/F cultivation compared to the flat surface land use systems is the complete change of water infiltration and fluxes on and in soils. Leaching of nutrients and other agrochemicals, which are susceptible to percolation, is strongly associated with water infiltration and subsequent water distribution. Bolton et al. (1970) found that the volume of water that flowed through the soil was the predominant factor responsible for N loss. Chen et al. (2011) also observed that the distribution of nitrate in the soil was similar to that of water.

Studies have shown varied results regarding the leaching of agrochemicals in R/F cultivation compared to other tillage systems. While some studies have shown a potential for increased leaching through the soil, other studies have shown that R/F cultivation reduced movement of agrochemicals (Hatfield et al., 1998). Drury et al. (1993) conducted a study to compare the effects of R/F cultivation, no tillage, and conventional tillage (CT) with mouldboard plow on nitrate loss through tile drainage in corn fields. Nitrate losses with tile drainage were with 10-16% of the applied total N greatest from CT compared to 8-11% under R/F cultivation as well as under no tillage treatment. Lower leaching losses under R/F cultivation were related to a lower volume of water flowing through the tiles, higher yields and higher N uptake. Hamlett et al. (1990) also found that less nitrate leached downward under uncropped R/F cultivation when compared to flat tillage. Loss of nitrate from the top 1.2 m of the soil was estimated to be about 10% (R/F cultivation) and 50% (flat tillage) of the application. In contrast to Drury et al. (1993), they found that the total downward water movement of both tillage systems was comparable. The lower N leaching losses were explained with the concentration of the fertilizer N in the ridges, which was by-passed by the infiltrating water due to surface flow from the ridges to the furrows. Kramer et al. (1990) and Kanwar et al. (1991), however, found increasing nitrate leaching losses under R/F cultivation and suggested that differences in water movement, namely the increased water infiltration and reduced surface runoff, were responsible for that finding. Leistra and Boesten (2010b) found that the surface flow of pesticides from the ridges into the furrows additionally increased the risk of pesticide leaching about the factor of 6 as compared to a level field.

Several studies observed a deeper or increased movement of agrochemicals in furrow soil compared to ridge soil due to localized water flow (Table 3). Leistra and Boesten (2008, 2010b) measured that the downward movement of broadcast applied bromide and carbofuran in furrow soils was distinctly greater than for the ridge soils. It was additionally observed that about 15% of the dosage was transported along the ridge surface to the furrows by rainfall and sprinkler irrigation. Computer simulations of the same field measurements by Leistra and Boesten (2010b) showed that bromide leached earlier, faster, and at higher concentrations from the furrows than from the ridges and that much of the bromide in the furrow soil had percolated before the roots had even developed there. Leaching of carbofuran (> 1 m depth) in the ridges was even found to be negligible, while leaching in the furrows was 1.5% of the application. Gaynor et al. (1987) also indicated deeper percolation for furrows. They found that the concentrations of atrazine and alachlor in the upper 10 cm of soil were 47% higher on the ridge tops than in the furrows one year after a broadcast application. However, no responsible mechanisms or factors were given. Smelt et al. (1982) measured a deeper leaching of the insecticide aldicarb in the furrows of a sandy soil than in the ridges and related this to the water repellency of the humic sandy topsoil and interception by the potato canopy. However, the highest amounts of aldicarb were in the ridges during the whole growing season due to the application process. The authors stated that stemflow under the natural rainfall of low intensity was not observed and hence, did not increase leaching in the ridges. Butters et al. (2000), however, found that under sprinkler irrigation stemflow might enhance leaching in the ridges by elevating ridge soil water content and reducing lateral flow into the ridges, which induces accumulation of bromide in the ridges. Under furrow irrigation, the authors did find 4-times higher retention of bromide in ridges compared to furrows, but indicated that the low concentrations in the irrigated furrow positions were a result of lateral movement to the ridge and dry furrow positions rather than of loss due to deep leaching. Chen et al. (2011) observed that the distribution of nitrate in the soil was dependent on ridge width. Deepest leaching of nitrate of all three ridge widths and deeper leaching under the furrows than under the ridges was measured under a ridge width of 30 cm. The deeper leaching under the furrows was related to the furrow irrigation. In contrast to Butters et al. (2000), no indication for lateral flow of the insecticide aldicarb and its compounds was found by Smelt et al. (1989). However, they found redistribution after tillage to be limited in general and indicated also only limited leaching. Butters et al. (2000) found that bromide movement under three irrigation treatments (sprinkler, every furrow, and alternate furrow) was dominated by lateral flow into the ridge and/or dry furrow positions. During dry periods, greater evaporation in the ridges than in the furrows enhanced the lateral flow into the ridges and the dry furrows. Under sprinkler irrigation, however, the authors observed stemflow that might enhance leaching in the ridges by elevating the soil water content of the ridges. The observed lateral flow into the ridges inducing accumulation of bromide in the ridges developed therefore slower under sprinkler irrigation than under furrow irrigation. Under alternate furrow irrigation, the authors found that the dry furrow did retain bromide, but it did so largely at the expense of ridge accumulation. However, the lateral flow of bromide into the ridge was found to sufficiently reduce downward leaching. In contrast, Clay et al. (1992) indicated a unidirectional flow in an uncropped R/F cultivation. When the agrochemical was applied in the furrows, the solute concentrations were correspondingly greater under the furrows than under the ridges. Jaynes and Swan (1999) also found only little indication for lateral tracer movement, when tracer was applied in the ridges. More than 96% of the ridge-applied tracer was found below the ridges. Lateral movement in furrows, however, was found to be more pronounced. Wadell and Weil (2006) observed that in the middle between planting and harvesting of corn, bromide moved together with the water towards the ridge tops due to a negative hydraulic gradient. Lateral movement of bromide was also contributed to an argilic soil horizon. However, generally bromide movement was indicated to be vertical. Hamlett et al. (1990) showed that nitrate moved vertically in the ridge and found only little indication for lateral movement from the fertilized to the unfertilized zones. They also indicated that the depth of the downward movement increased with amount of rain. For 24 mm rainfall simulation, only little downward movement of nitrate was measured. For the two higher rainfall simulations, greater downward movement of nitrate was observed.

6 Approaches for decreasing solute leaching under R/F cultivation

Plant residue cover is used in R/F cultivation to reduce soil erosion and losses in the furrows. Plastic mulches covering the ridges are used for weed control. To reduce the potential of leaching in R/F cultivations, some studies suggest isolating the agrochemicals from the infiltrating and percolating water. The idea is to place agrochemicals precisely into the ridges. The irrigation water or rainfall bypasses the agrochemical banded in the ridge due to increased furrow infiltration and the agrochemical is therewith protected against downward percolation with infiltrating water. Weed et al. (1995) also suggested that the number of preferential flow pathways through the soil and hence the potential for leaching could be reduced when pesticides and N were placed in the ridges. The protection of water quality might be a significant factor for future adoption of the R/F cultivation (Hatfield et al., 1998).

Already in the 1970s, Kemper et al. (1975) investigated the fertilizer movement from ridges under furrow irrigation. The authors demonstrated that the ridge-applied fertilizer delayed nitrate leaching compared to broadcast application, when the fertilizer was banded above the water level in the irrigated furrows. While these findings were proved true even at very high rates of irrigation, nearly all the nitrate was leached, when the fertilizer was applied below the water level of the irrigated furrow. Hamlett et al. (1990) demonstrated for uncropped R/F cultivations that the total nitrate movement was reduced at three different amounts of rainfall, when nitrate was placed in the ridges. However, with increasing rain amounts, the downward movement of nitrate in the ridge increased as well and the amount of nitrate at the point of application concurrently decreased. Clay et al. (1992) also indicated that leaching was influenced by placement technique in an uncropped R/F cultivation system. They compared the leaching of three substances, which were either band applied to the ridge top or in the furrow. In the ridge-applied treatment, more N fertilizer was recovered in the upper 30 cm of soil (70%) than in the furrow-applied treatment (28%). Blaylock and Cruse (1992) found no consistent differences in leaching between point injected nitrate in ridges or furrow in a R/F maize cultivation. The method of fertilizer application might be an explanation for the differences in these two studies. Clay et al. (1992, 1994) reported that the method of fertilizer application must not result in the formation of secondary microrelief features that increase local infiltration. They found that the injection slots created in the ridges might negate or reverse the reducing effect of ridge placement on leaching. Benjamin et al. (1994, 1998) tested another variation of isolating agrochemicals from infiltrating water. They placed the chemical in the non-irrigated furrow of an alternate-furrow irrigation system. While the solute movement was detected to be least with alternate-furrow irrigation and placement of the agrochemical under the non-irrigated furrow, it was also implied that the agrochemicals placed there might not be available for plant uptake because the soil did not wet during irrigation. Based on these findings, they recommend for both furrow irrigation systems the placement of chemicals in the ridges as it keeps the chemical in the root zone of the plants. Waddell and Weil (2006) also found a better uptake of agrochemicals for ridge-applied chemicals than for furrow-applied chemicals. However, their findings imply that stemflow might increase the rain infiltration into the ridge and increase the potential of solute leaching in the ridges compared to furrow application. This effect was only observed in the mid-growing season. At the beginning of the growing season and after harvest, when crops were either small of not emerged yet, stemflow caused less leaching in the ridge tops.

We conclude that a reliable reduction of water and nutrient leaching can be achieved by the combination of these approaches. Such combinations may include: 1) placement of fertilizers on or in the top of ridges, 2) covering the ridges with PE mulch to decrease downward water flow at places with high fertilizer content, and 3) the stimulation of fast root growth.

7 Conclusions and Outlook

As this literature overview shows, there are several factors, which can be of great significance whether R/F cultivation and the placement of agrochemicals reduce or even enhance leaching. It was shown that placing agrochemicals in the ridges alone did not reduce leaching as a matter of principle. Under natural rainfall or sprinkler irrigation, factors like stemflow and secondary microtopography might have great impact. However, placing agrochemicals separately from the infiltrating water showed promising success, but influencing factors will have to be quantified in future. To quantify water infiltration patterns, subsoil water fluxes, and subsequent leaching losses is complicated. Some of the studies investigated water flow and leaching potential in uncropped fields. However, type of crop and crop growth are factors significantly affecting infiltration, evaporation and soil water content. Soils with water repellent horizons additionally alter the water infiltration and flow. Small alterations of the microtopography, like slots created from point injection of fertilizer, might negate or reduce possible positive effects. Modifications of the ridges, such as width, height and cover can play an important role in changing microtopography and concurrently water infiltration and flows. Another important potential of leaching redction is the irrigation method and volume. While sprinkler irrigation and natural rainfall can result in stemflow and hydrophobic soil layers, which alter the infiltration of water into the soil, furrow irrigation often results in overirrigation in the need to apply sufficient water to replenish the root zone of the soil farthest from the water source. The multitude of factors influencing infiltration as well as water and solute fluxes is a huge challenge for measuring, analyzing and modeling. This is especially pronounced in humid climates and climates with uneven distribution of precipitation (Asian monsoon or Mediterranean climates). Variability in amount, intensity, duration, and frequency of natural rainfall events are a great challenge for measurements in the field but also for modeling. Up to now, precise quantification of surface transport of water and substances from the ridges to the furrows at different conditions is scarce.

Table 2 Compilation of published studies investigating water flow in R/F cultivation

Author	Soil	R/F configuration	Irrigation	Crop	Main infiltration in furrow	Vertical/horizontal water movement	Wetting of ridge	Stemflow, water repellency
Chen et al. 2011	Clay loam	Permanent Ridge height: 15cm Spacing: 60cm	Furrow irrigation	Uncropped	+	Vertical dominant/ Delayed lateral	Dependent on ridge width	X
Bargar et al. 1999	Loam, silt-loam	Permanent Ridge height: 8-11cm Spacing: 76-97cm	No irrigation	Uncropped	+	Vertical dominant/ Delayed lateral	X	Soil sealing
Hamlett et al. 1990	Loam	Temporal Spacing: 76cm	Rainfall simulation	Uncropped	+ (water ponding)	Vertical dominant/ Only little lateral	X	X
Leistra and Boesten 2008 and 2010	Sand	Temporal Ridge height: 20cm Spacing:75cm	Sprinkler	Potato	+	Vertical/ x	x	X
Dekker and Ritsema 1996	Sand	Temporal	Sprinkler	Potato	+ (water ponding)	X	Only partly	Stemflow
Waddell and Weil 1996, 2006	Sandy loam	Permanent	Rainfall simulation	Corn	+ (before crop emergence and after harvest)	Vertical dominant/ Lateral movement during midseason	Dry ridge tops	Stemflow
Cooley et al. 2007	Loamy sand	Temporal Ridge height: 15cm Spacing: 90cm	Sprinkler (compared to drip)	Potato	+	X	Dry zone in center	Hydrophobic soil, Stemflow
Robinson 1999	Sand	Temporal Ridge height: 20cm Spacing: 75cm	Sprinkler	Potato	+ (amplified by water repellent soil)	X	Dry zone in center	Water repellency, Stemflow
Clay et al. 1992	Sandy loam	Permanent Ridge height: 7-8cm Spacing: 45cm	Rainfall simulation	Uncropped	+ (water ponding)	X	X	X
Starr et al. 2005	Loamy sand	Temporal	Sprinkler	Potato	+	Vertical/x	Wetted poorly	X

Table 3 Compilation of published studies investigating leaching of agrochemicals in R/F cultivation. SI = Sprinkler irrigation; EFI = each furrow irrigation; AFI = Alternate furrow irrigation

Author	Soil + Crop	R/F configuration	Irrigation	Agrochemical and placement	Increased leaching in furrow	Reduced leaching in ridge	Dominant flow direction	Leaching potential
Leistra and Boesten 2008/ 2010	Sand Potato	Temporal Ridge height: 20cm Spacing: 75cm	SI	Bromide and carbofuran; both broadcast	+ (surface transport from ridge to furrow)	+	Vertical (+surface flow)	> Flat tillage
Butters et al. 2000	Clay loam Corn	Permanent Spacing: 76cm	SI, EFI, AFI	Bromide broadcast	+ (SI) - (EFI, AFI)	- (SI) + (EFI, AFI)	Lateral (EFI, AFI) Lateral (SI)	SI > EFI = AFI
Smelt et al. 1981	Sand, Loam Potato	Temporal Ridge height: 20cm Spacing: 75cm	Rainfall	Nematicide aldicarb Broadcast before ridging	+ (water repellency of sand)	+	Vertical	Low
Clay et al. 1992	Sandy loam Uncropped	Permanent Ridge height: 7-8cm Spacing: 45cm	Rainfall simulation	Alachlor, bromide, and calcium nitrate Banded in ridge top or furrow	+	+	Vertical	Banding on ridge top < banding in furrows
Jaynes and Swan 1999	Silt loam, loam Uncropped	Permanent Ridge height: 8-11cm Spacing: 76-97cm	Natural rainfall	Bromide, anionic dyes Ridge top, ridge shoulder or furrow	+ (furrow-applied)	+ (ridge-applied)	Vertical (ridges) Lateral (furrows)	Ridge placement < furrow placement
Hamlett et al. 1990	Loam Uncropped	Temporal Spacing: 76 cm	Rainfall simulation	Nitrate, bromide Ridge placement	X	+	Vertical	< Flat tillage
Waddell and Weil 2006	Sandy loam Corn	Permanent	Rainfall simulation	Bromide, nitrate Banded in ridge top or furrow	X	- (due to stemflow)	Vertical Lateral (in midseason)	Ridge placement < furrow placement

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I hereby declare that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis. This thesis contains no material which has been accepted or definitely rejected for the award of any other doctoral degree in any other university or equivalent institution.

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