Estimation and mitigation assessment of N_2O emission and nitrate leaching in a mountainous catchment in South Korea using the LandscapeDNDC model

Dissertation

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Youngsun Kim

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Acting director:

Prof. Dr. Franz Xaver Schmid

Doctoral committee:

Prof. Dr. John Tenhunen (first reviewer)

PD. Dr. Ralf Kiese (second reviewer)

Prof. Dr. Christoph Thomas (chairman)

Prof. Dr. Bernd Huwe

Abstract

The application of excessive N fertilizer is a common farming practice in Southeast Asia to ensure the optimum crop yield. However, surplus N in soil induced from higher fertilization than crop N demand is highly susceptible to loss as N_2O emission and nitrate leaching during heavy rainfall events in the monsoon season. Intensive farming conducted in the Haean catchment of South Korea has received much attention due to its geographical importance as an upstream region of the Soyang River Dam, which is used as the major drinking water for urban residents (including Seoul). Taking into account the combination of monsoon climate, intensive N fertilizer use and sand dressing prior to mulching and seeding of upland fields in the Haean catchment are likely to cause significant N loss and soil erosion, which have a high potential for directly impacting on the dam water quality via the Mandae stream.

The plastic mulch as well as high N fertilization is a typical agricultural management practice for upland crop cultivation in the Haean catchment. To consider effects of plastic mulch on the dynamics of soil temperature and water content, based on soil measurements, meteorological input data i.e. air temperature and precipitation were adjusted to allow the biogeochemical LandscapeDNDC model differentiating simulations of plastic mulch (row) conditions. Furthermore, the actual weather data was applied for the simulation of interrow conditions. The main parameters such as MaxTDD, Tlimit, OptYield and WUECMAX for the simulation of plant growth of major upland crops (i.e. potato, radish, soybean and cabbage) and dominant tree species (i.e. *Quercus Mongolica*) of the Haean catchment were newly implemented into the model. Taking into account mulching effects and different agricultural management practices, the LandscapeDNDC was validated against detailed field measurements of N_2O emission, nitrate concentration, soil temperature and water content (5, 15 and 30 cm soil depth) and biomass production from potato, radish, soybean and cabbage fields. Furthermore, the LandscapeDNDC was also tested against field data of N_2O emission, soil temperature and water content (10 cm soil depth) from temperate deciduous forest sites located at three different altitudes and thus different exposure to atmospheric N deposition (24 - 51 kg N ha^{-1}). Application of the adjusted meteorological data showed better prediction of soil temperature and water content from rows covering with plastic mulch as compared to application of the actual weather data (e.g. adjusted data: r^2 = 0.49; actual data: r^2 = 0.18). Developmental stages of major upland crops were successfully captured by the LandscapeDNDC and separately simulated above- and belowground biomass were in good agreement with measured biomass (r^2 = 0.81 - 0.98). The peak N_2O emissions after N fertilization from potato, radish and cabbage fields were generally underestimated, however, with respect to high uncertainties and low frequency of measurements, temporal dynamics and magnitude of N_2O emission (r^2 up to 0.45; ME up to 0.21) as well as nitrate concentration (r^2 up to 0.89; ME up to 0.43) were well captured by the model. Based on the

successful site validation, the LandscapeDNDC was connected to a GIS database holding all spatially explicit information on climate, soil, vegetation and management and used for estimating N_2O emission, nitrate leaching and crop production from intensively managed upland fields and temperate deciduous forest of the Haean catchment (61.5 km²).

The main objectives of this thesis were to estimate N_2O emission, nitrate leaching and crop yield from the Haean catchment taking into account different land use and environmental conditions and to evaluate mitigation options to minimize N losses while maintaining the current crop yield. The LandscapeDNDC simulation of the mean annual direct N_2O emissions from upland fields and temperate deciduous forest was 2.03 and 0.50 kg N ha^{-1} through 2009 - 2010, respectively. Simulated mean nitrate leaching rates from upland fields resulted in much higher annual values of 112.2 and 125.4 kg N ha^{-1} in 2009 and 2010, respectively. In contrast, simulated mean nitrate leaching rates from temperate deciduous forest were negligible ($\leq$ 0.01 kg N ha^{-1} yr^{-1}) both in 2009 and 2010. Direct N_2O emission factors for upland fields of the Haean catchment were 0.80 and 0.94% in 2009 and 2010, respectively, which is slightly lower than the IPCC default value of 1%. However, due to the high nitrate leaching rate estimated indirect N_2O emission from nitrate leaching was substantial and was in the similar range of direct N_2O emission from upland fields. Simulated upland crop biomass ranged between 5.5 and 17.8 t DW ha^{-1} with annual mean values of 10.4 and 9.3 t DW ha^{-1} in 2009 and 2010, respectively. Estimation of area-weighted total N_2O emission (sum of direct and indirect N_2O emissions) from the Haean catchment was 3.31 and 2.93 t N yr^{-1} in 2009 and 2010, respectively. About 52% of the total N_2O emission was derived from fertilized upland fields, covering only 27% of the catchment area. The model predicted nitrate leaching as the dominant pathway of N loss from the Haean catchment with annual values of 72.0 and 59.5 t N yr^{-1} in 2009 and 2010, respectively. Fertilized upland fields were the strongest source of nitrate leaching, which accounted for 99% of simulated total nitrate leaching from the Haean catchment through 2009 - 2010. Mainly due to the decrease in total N fertilization rate in response to the reduction of cultivation area, N_2O emission and nitrate leaching were about 14% lower in 2010 as compared to 2009.

Adopted mitigation options were based on the maximum reduction of nitrate leaching and N_2O emission without penalizing the current crop yield. Generally simulations show that N export to the environment could be reduced by overall lowering of fertilization rates by approximately 34% without impacting on current crop yields. Splitting N fertilizer application into 3 times rather than 2 times showed slightly higher potential for minimizing N loss from upland fields of the Haean catchment. By splitting N fertilizer application into 3 times the total nitrate leaching could be significantly reduced by 68% (32.7 t N yr^{-1}) in 2009. Even a higher reduction rate of 78% was achieved for the year 2010. Reduced nitrate leaching would significantly decrease mean nitrate concentrations in the Mandae stream at the Haean catchment outflow from 3.5 to about 2 mg l^{-1}, which is much closer to the quality standard of inland water of 1.5 mg l^{-1}. Estimated mitigation of N_2O emissions from upland fields was 0.93 and 0.78 t N yr^{-1}, which was about 49 and 52% reduction in N_2O emissions as compared to farmers` practices in 2009 and 2010, respectively. Taking into account a 47 ton reduction in N fertilization by the adopted mitigation option, fertilizer-induced N loss (sum of nitrate leaching rate and N_2O emission) from upland fields of the Haean catchment was projected to decrease significantly by 73% as compared to the N loss from the farmers` practices through 2009 - 2010.

To the best of our knowledge this was the first study of upscaling N_2O emission and nitrate leaching including assessment of mitigation options in order to reduce N loss from a catchment in South Korea with a process based biogeochemical model. The most remarkable finding of this thesis was to show the significant potential for decreasing N loss without affecting the current crop yield by the application of adopted mitigation option. However, further studies are still required to evaluate additional mitigation options such as cover crops (e.g. rapeseed and winter wheat which have been already started by a cultivation experiment in Gangwon Province) and reduced tillage both potentially contributing also to increase of soil carbon stocks and soil fertility. Furthermore, adaptation of fertilizer management with fertilization only into the plant holes of rows and adjustment of timing of fertilization depending on accurate weather predictions, which can be particularly important under monsoon climate conditions. The finding of this study could be suggested as guidelines for improving farmers` practices while minimizing the N loss from the entire crop field of the Haean catchment.

Zusammenfassung

Übermäßige Stickstoffdüngung ist in weiten Teilen Südost-Asien gängige landwirtschaftliche Praxis, um optimale Ernten zu gewährleisten. Düngung über den Pflanzenbedarf hinaus führt jedoch dazu, dass insbesondere in der Monsoon-Zeit, überschüssiger Stickstoff aus den Böden in Form von Nitrat (NO_3) ausgewaschen oder als N_2O in die Atmosphäre emittiert werden kann. Der intensiven Landwirtschaft im Haean-Becken in Südkorea kommt große Aufmerksamkeit zu, da dieses Einzugsgebiet über den Mandae-Fluss den Soyang River Dam speist, welcher zur Trinkwassergewinnung für die umliegende städtische Bevölkerung (inklusive Seoul) dient. Die Kombination von Monsunklima, intensiver Stickstoffdüngung, Topdressing mit Sand und Mulchen der Felder mit Plastikfolie im Haean Einzugsgebiet, lässt einen signifikanten Austrag von Stickstoffin die Umwelt und Bodenerosion vermuten, die sich negativ auf die Wasserqualität des Soyang River Dams auswirken.

Mulchen mit Plastikfolie, sowie starke Stickstoffdüngung sind typische landwirtschaftliche Praktiken für den Feldfruchtanbau im Haean-Becken. Um die Effekte des Plastikmulchens auf die Dynamik der Bodentemperatur und des Bodenwassergehalts zu berücksichtigen, wurden basierend auf Bodenmessdaten meteorologische Inputdaten wie Lufttemperatur und Niederschlag so angepasst, dass das biogeochemische LandscapeDNDC Model die Bedingungen in den mit Plastikfolie bedeckten Pflanzenreihen besser simulieren konnte. Die tatsächlichen Wetterdaten wurden verwendet um die Bedingungen zwischen den Pflanzreihen zu simulieren. Weiterhin wurde das LandscapeDNDC Model erweitert, um das Pflanzenwachstum für diese Studie wichtige Feldfrüchte wie Kartoffeln, Rettich, Sojabohnen und Kohl, sowie die im Hean Einzugsgebiet dominierende Baumart *Quercus mongolica* simulieren zu können. Hierzu wurden insbesondere die Hauptparameter für das Pflanzenwaschstum, wie MaxTDD, Tlimit, OptYield und WUECMAX angepasst. Das für die spezfischen landwirtschaftlichen Praktiken wie Mulchen angepasst LandscapeDNDC Modelwurde im nächsten Schritt mit detailierten Feldmessungen von N_2O-Emissionen, NO_3^--Konzentrationen, Bodentemperatur und Bodenwassergehalt (in 5, 15 und 30 cm Bodentiefe) und Biomasseproduktion von Kartoffel-, Rettich-, Sojabohnen- und Kohlfeldern validiert. Außerdem wurde das Model auch mit Messungen von N_2O-Emissionen, Bodentemperatur und Bodenwassergahlt (in 10 cm Bodentiefe) temperater Laubwälder in drei verschiedenen Höhenlagen und somit unterschiedliche Raten der Stickstoffdeposion (24 - 51 kg N ha^{-1}), getestet. Die Verwendung des angepassten meteorologischen Inputdatensates führte zu einer besseren Vorhersagbarkeit von Bodentemperatur und -Wassergehalt in mit Plastikfolie bedeckten Beeten als die Anwendung der für diese Verhältnisse unrealistischeren tatsächlichen Wetterdaten (angepasste Daten: $r^2 = 0.49$; tatsächliche Daten: $r^2 = 0.18$). Die Biomassen der verschiednenen Entwicklungsstadien der wichtigen Feldfrüchte wurde erfolgreich vom Model erfasst und seperat modellierte oberirdische und

unterirdische Biomasse waren ebenso in gutem Einvernehmen mit der im Feld gemessenen Biomasse (r^2 = 0.81 - 0.98). Die N_2O-Emissionspitzen nach der Stickstoffdüngung von Kartoffel-, Rettich und Kohlfeldern wurden generell unterschätzt. In Anbetracht relativ hoher Unsicherheiten und der niedrigen Messfrequenz der Messwerte, wurde jedoch die zeitliche Dynamik und Menge der N_2O-Emissionen (r^2 bis zu 0.45; ME bis zu 0.21) generell gut vom Model erfasst. Die Simulationen der zeitlichen Veränderung der Nitratkonzentrationen in verschiedenen Bodentiefen stimmten ebenso gut (r^2 bis zu 0.89; ME bis zu 0.43) mit Messwerten überein. Basierend auf der erfolgreichen Validierung auf Plot-Skale, wurde das LandscapeDNDC Model an eine GIS-Datenbank gekoppelt, welche räumlich explizite Informationen über Klima, Boden, Vegetation und Managementpraktiken vorhält, und verwendet um N_2O-Emissionen, NO_3^--Auswaschung und Ernteerträge von intensiv bewirtschafteten Feldfrüchten und Laubwäldern des Haean-Beckens abzuschätzen (61.5 km^2).

Die Hauptzielstellungen dieser Arbeit waren das Abschätzen von N_2O-Emissionen, NO_3^--Auswaschung und Ernteerträgen im Haean-Becken unter Berücksichtigung verschiedener Landnutzung- und Umweltparameter und die Evaluierung von Optionen um Stickstoffverluste bei gleichbleibend hohen Ernteerträgen zu mindern. Die LandscapeDNDC-Simulation der mittleren jährlichen N_2O-Emissionen der Felder und Laubwälder waren 2.03, beziehungsweise 0.50 kg N ha^{-1} für den Zeitraum 2009 - 2010. Simulierte mittlere NO_3^--Auswaschungsraten ergaben viel höhere Werte von 112.2, beziehungsweise 125.4 kg N ha^{-1} für den Zeitraum 2009 - 2010. Im Kontrast dazu waren die simulierten mittleren NO_3^--Auswaschungsraten der Laubwälder für den gleichen Zeitraumvernachlässigbar klein ($\leq$ 0.01 kg N ha^{-1} yr^{-1}). Die direkten N_2O-Emissionsfaktoren des Feldfruchtanbaus im Haean-Beckens waren 0.80 und 0.94% für 2009 und 2010, was geringfügig unter der IPCC-Vorgabe von 1% liegt. Allerdings waren die indirekten N_2O-Emission in Folge von NO_3^--Auswaschung substanziell höher und vergleichbar der Größenordnung der direkten N_2O-Emissionen. Die simulierte Feldfruchtbiomasse lag zwischen 5.5 und 17.8 t DW ha^{-1} mit jährlichen Mittelwerten von 10.4 und 9.3 t DW ha^{-1} für 2009 und 2010. Eine Abschätzung von auf die Fläche bezogenen N_2O-Emissionen (Summe aus direkter und indirekter N_2O-Emission) des Haean-Beckens ergab 3.31, beziehungsweise 2.93 t N yr^{-1} für 2009 und 2010. Dabei stammen 52% der gesamten N_2O-Emissionen von den gedüngten Feldern, welche flächenmäßig nur 27% des Haean-Beckens ausmachen. Die Model-Simulationen zeigen, dass die NO_3^--Auswaschung der dominante Weg für Stickstoffverluste im Haean-Becken darstellt, mit jährlichen Werten von 72.0, beziehungsweise 59.5 t N yr^{-1} für 2009 und 2010. Gedüngte Felder waren die größte Quelle für ausgewaschenes NO_3^- und bedingten 99% der gesamten simulierten NO_3^--Auswaschung des Haean-Beckens im Zeitraum von 2009 - 2010. Verursacht durch eine Abnahme der gesamten

Stickstoffdüngungsrate als Folge einer Verringerung der gesamten kultivierten Fläche, waren N_2O-Emissionen und NO_3^--Auswaschung im Jahr 2010 um 14% geringer als 2009.

In dieser Studie angewandte Mitigations-optionen basierten auf der maximalen Reduzierung von NO_3^--Auswaschung und N_2O-Emissionen ohne nachteilige Auswirkung auf die derzeitigen Erntebeträge. Die Simulationen zeigen, dass generell niedrigere N-Düngegaben zu einer deutlichen Reduzierung des N-Austrags in die Umwelt führen, ohne Auswirkungen auf die derzeitige Höhe der Ernteerträge. Verglichen mit zwei Applikationszeitpunkten würde die Ausbringung des Stickstoffdüngers zu drei Zeitpunkten zu einer höheren Reduzierung der Stickstoffverluste von den Feldern des Haean-Beckens führen. Bei drei Düngungszeitpunkten war die modellierte Gesamt-NO_3^--Auswaschung für 2009 um 68% geringer (32.7 t N yr^{-1}). Für 2010 ergab sich sogar eine Reduzierung um 78%. Diese reduzierte NO_3^--Auswaschung würde die NO_3^--Konzentrationen im Abfluss des Mandae-Flusses von 3.5 auf 2 mg l^{-1} verringern, was deutlich näher am für Binnengewässern festgelegten Qualitätsstandard-Wert von 1.5 mg l^{-1} liegt. Die abgeschätzte Minderung der N_2O-Emissionen aus landwirtschaftlichem Anbau betrug 0.93 und 0.78 t N yr^{-1}, was eine Reduzierung um 49% für 2009 und 52% für 2010 ergeben würde. Unter der Annahme einer reduzierten Stickstoffdüngung von 47 Tonnen bei der vorgeschlagenen Milderungsoption, wäre der durch Düngung induzierte Stickstoffverlust (Summe aus NO_3^--Auswaschung und N_2O-Emissionen) um 73% geringer gewesen als im Vergleich zum Stickstoffverlust, der durch die Feldmanagementpraktiken 2009 und 2010 tatsächlich aufgetreten ist.

Unseres Wissens nach, ist dies die erste Studie, in der N_2O-Emissionen und NO_3^--Auswaschung, sowie Vorschläge für Milderungsstrategien um Stickstoffverluste zu reduzieren, regional für ein Wassereinzugsgebiet in Südkorea mit einem prozessbasierten biogeochemischen Modell abgeschätzt wurden. Das bedeutendste Resultat dieser Studie ist das Aufzeigen des hohen Potenzials von Minderungsstrategien, Stickstoffverluste zu reduzieren ohne Ernteerträge zu beeinträchtigen. Jedoch sind weitere Studien notwendig, um weitere Optionen wie Gründüngung (Raps und Winterweizen, welche in einem Bepflanzungsexperiment in der Kangwon-Provinz bereits getestet werden) und reduziertes Pflügen, zu evaluieren. Beide Praktiken tragen weiterhin dazu bei die Boden-Kohlenstoffgehalte und damit die Bodenfruchtbarkeit zu erhöhen. Außerdem würde eine veränderte Düngungspraxis mit Düngergaben direkt in die Pflanzlöcher unter Berücksichtigung von aktuellen Wetterprognosen, vor allem während der Monsunwetterlage, weitere Milderungen des N-Austrags ermöglichen. Die Ergebnisse dieser Studie könnten als Basis zur Modifizierung der derzeitigen landwirtschaftlichen Praxis von Landwirten im Haean Einzugsgebiet dienen, um Stickstoffverluste in die Umwelt stark zu verringern.

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List of abbreviations

BD	Bulk Density
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
DEM	Digital Elevation Model
DNDC	DeNitrification and DeComposition
DW	Dry Weight
FAO	Food and Agriculture Organization
FC	Field Capacity
GHG	Greenhouse Gas
GIS	Geographical Information System
IPCC	Intergovernmental Panel on Climate Change
KEEI	Korea Energy Economics Institute
MAFRA	Ministry of Agriculture, Food and Rural Affairs
Max	Maximum
MaxTDD	Sum of daily temperature necessary for complete crop development
ME	Model Efficiency
Min	Minimum
N	Nitrogen
N_2O	Nitrous oxide
N_2O EF_d	direct N_2O Emission Factor
NH_3	Ammonia
NH_4^+	Ammonium
NO_3^-	Nitrate
NUE	Nitrgen Use Efficiency
O_2	Oxygen
OptYield	Maximum yield under optimum condition
p	Probability
PE	PolyEthylene
r^2	Coefficient of determination
RDA	Rural Development Administration

$RMSPE_n$	Normalized Root Mean Square Prediction Error
SF	Stone Fraction
SOC	Soil Organic Carbon
SS	Suspended Solids
TERRECO	Complex TERRain and ECOlogical Heterogeneity
Tlimit	Minimum temperature for plant growth
TN	Total Nitrogen
TP	Total Phosphorus
Vol	Volume
WP	Wilting Point
WUECMAX	Maximum water use efficiency

Chapter 1

Synopsis

1.1 Introduction

Agriculture represents the largest anthropogenic source of N_2O, which is one of the most important non-CO_2 greenhouse gases. Global N_2O emissions from agriculture are expected to increase up to 7.6 Tg N_2O-N yr^{-1} by 2030 due to the increase of N fertilizer use in Africa, Asia and Latin America (Reay et al. 2012). The increase of anthropogenic N input including chemical fertilizer, animal waste and other organic fertilizer, crop residue, etc. is a major factor enhancing N_2O emissions (IPCC 2000). The world consumption of N fertilizer has increased by 150% since 1970 and is projected to be 116 million tons in 2016 (FAO 2012; IPCC 2000). Of the global consumption of N fertilizer, Asia is the world`s largest consumer (62%) of N fertilizer (FAO 2012). The fertilizer consumption in South Korea is 2.5 times higher than the world average fertilizer consumption of 132 kg N ha^{-1} (Alexandratos and Bruinsma 2012) even though the fertilizer consumption in South Korea has decreased by 28% in 2012 as compared to a decade ago (MAFRA 2013).

About 24% of national N_2O emissions in South Korea is induced by agriculture and agricultural soils are the major source of N_2O emissions, accounting for 59% of the total N_2O emissions in agriculture (KEEI 2009b). N_2O is an intermediate product of nitrification and denitrification processes, which is regulated by substrate availability, pH, soil temperature and water content (Chapuis-Lardy et al. 2007; Mosier et al. 1998). With these soil environmental factors, agricultural management practices such as type and timing of N fertilizer, plastic mulch and tillage influence on soil N_2O emissions as well as nitrate leaching and NH_3 volatilization (Bouwman et al. 2002a; Kim et al. 2014; Nishimura et al. 2012). Arable land in Korea is relatively small, which covers only 17.3% of the total area of South Korea (MAFRA 2013). Korean agriculture has been characterized as excessive use of N fertilizer due to the expectation of high crop yields from this small cultivation area. The survey of fertilizer use in Gangwon Province showed that 59.8% of the local farmers (total participants = 241) have applied 1.3 to 3 times more fertilizer and even 1.2% of them have added 4 times more fertilizer than the recommended rate (Gangwon-do 2006). Considering 94% of uplands in Gangwon Province (≥ 400 m a.s.l) located near the Han River Watershed (Lee et al. 2007; Shin et al. 2005b), which is a major drinking water source of 24 million metropolitan residents, the high application rates of N fertilizer have significant potential risks on this water source.

The application of black polyethylene mulch film for upland crop cultivation is typical farming management with the intensive fertilization in South Korea. Due to the benefits of plastic mulch such as improving crop yield, reducing fertilizer loss and soil surface evaporation and regulating soil temperature (Fisher 1995; Ghosh et al. 2006; Romic et al. 2003), it has been widely used in many other countries in the world. For example, in Northern China, facing a shortage of water, plastic mulch is a significant farming practice to save water and improve crop yields (Wang et al. 2009a; Xie et al. 2005). Despite of many field studies focusing on soil environmental factors, nutrient losses and crop production under plastic mulch (Chakraborty et al. 2010; Ibarra et al. 2001; Li et al. 2004b; Nishimura et al. 2012; Ramakrishna et al. 2006), to the best of our knowledge few modeling research has considered the plastic mulch in the models due to the complicated interaction between the plastic mulch and soil environmental condition and plant physiology. In this thesis, the LandscapeDNDC model (Haas et al. 2013) was adopted, applied and validated against field measurements of soil temperature and water content, biomass production, N_2O emission and nitrate concentration in rows with plastic mulch and interrow without mulch of upland crop fields in the Haean catchment, South Korea.

Study 1: Site scale simulation of radish cultivation under plastic mulch

Radish is the third leading upland crop in South Korea (MAFRA 2013). It is a short duration crop with a high demand for nutrients cultivated under plastic mulch in the cool season (Akoumianakis et al. 2011; El-Desuki et al. 2005). Due to a high growth rate and a rapid return of capital (Cortez et al. 2010; Hegde 1987), farmers usually apply high rates of N fertilizer to increase the marketable yield of radish. The first study (Chapter 3) focused on adaptation and application of the LandscapeDNDC model to the typical farming system in South Korea. The objectives of this study were to test the LandscapeDNDC for simulation of soil temperature and water content, crop growth, N_2O emission and nitrate leaching from radish cultivation under plastic mulch and investigate the effects of plastic mulch while comparing simulation results between row and interrow. Previous studies have shown that plastic mulch increases soil temperature and restricts the penetration of precipitation into the soil so that N_2O emission is enhanced but nitrate leaching rate is reduced (Nishimura et al. 2012; Romic et al. 2003; Zhang et al. 2012). Therefore, the hypotheses were set up as follows:

1) N_2O emission is higher under plastic mulch as compared to no-mulch.

2) Plastic mulch is effective in reducing nitrate leaching rate due to inhibiting the penetration of rainfall into the soil.

Study 2: Regional scale simulation of major upland crop fields and temperate deciduous forest and assessment of mitigation options

In conjunction with radish, potato, soybean and cabbage are the major upland crops, accounting for about a half of the total upland area (Yanggu-gun 2011; 2012) of the Haean catchment. The first study (Chapter 3) showed the potential of LandscapeDNDC for differentiating between plastic mulch (row) and no-mulch (interrow) simulation of the radish field. Based on the results of the site scale simulation, the second study (Chapter 4) was conducted on the catchment scale with simulation of major upland crops, considering various agricultural management practices and environmental conditions. Approximately 60% of the Haean catchment is covered by forest. Taking into account broadleaved trees as the dominant species covering 60% of the catchment area (TERRECO, unpublished data), the LandscapeDNDC model was tested against three forest sites located at different altitudes (450, 650 and 950 m a.s.l) and then extended also to the simulation of the entire forest area of the Haean catchment. The aims of this study were to estimate N_2O emission, nitrate leaching and biomass production from the Haean catchment and evaluate potential mitigation options, which could reduce environmental N loads (N_2O emission and nitrate leaching) without reducing crop yields. The hypotheses were set up as follows:

1) Nitrate leaching is the dominant pathway of N loss from upland fields of the Haean catchment.

2) Reduction in fertilization rate with splitting fertilizer application is effective in decreasing N_2O emission and nitrate leaching from upland fields of the Haean catchment.

1.2 Materials and methods

1.2.1 Description of study region

The study was performed at the Haean catchment (38° 19' 34" N, 128°10' 25" E, 400 - 1100 m a.s.l), Yanggu County, Gangwon Province, South Korea. The Haean catchment (ca. 62 km^2) consists of forest (59%), cropland (36%) and residential area and other land uses (5%) (Yanggu-gun 2012) (Figure 1.1). According to the extensive field survey conducted within the scheme of the TERRECO project (GRK 1565/1), the deciduous forest covers almost the entire forest area of the Haean catchment and less than 1% is occupied by the coniferous forest. Agriculture is the primary industry, with upland fields covering about 76% of the total agricultural area of the Haean catchment. Half of the total upland area is used for major upland crop cultivation such as potato (*Solanum tuberosum* L.), radish (*Raphanus sativus* L.), soybean (*Glycine max* L.) and cabbage (*Brassica oleracea* var. *capitata* and *Brassica rapa* var. *glabra*) (Yanggu-gun 2011; 2012).

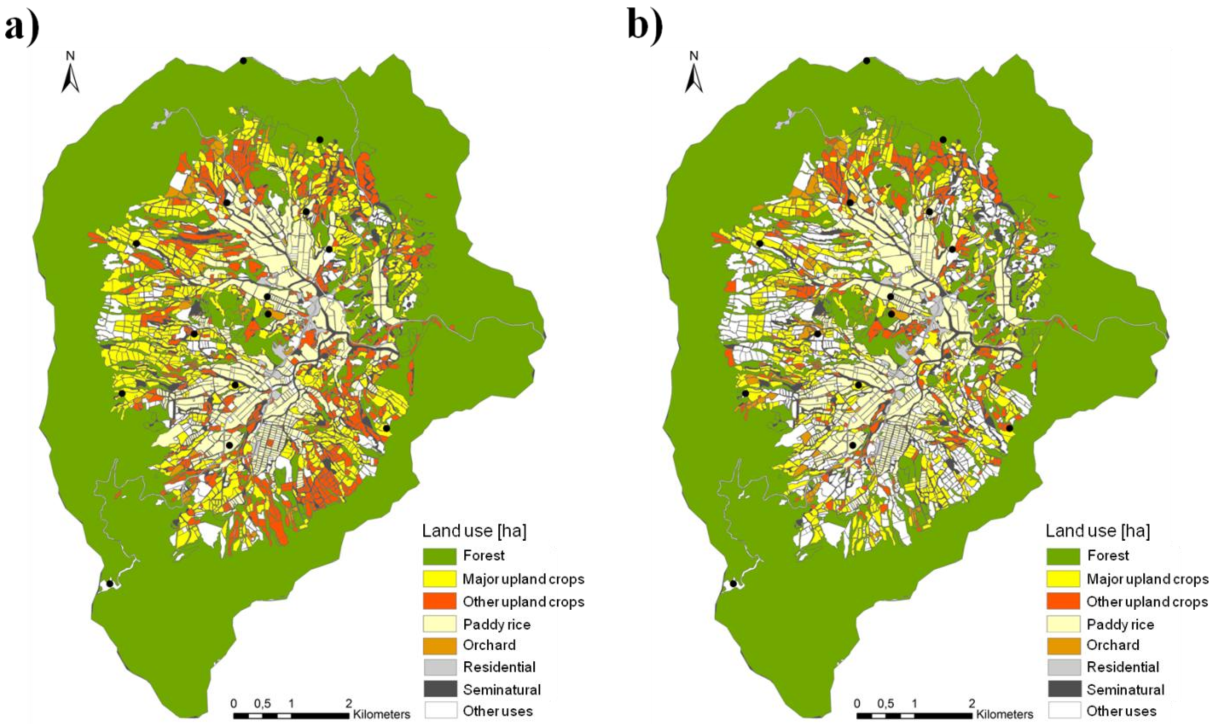

Figure 1.1 Land uses of the Haean catchment in a) 2009 and b) 2010. Forest is the dominant land use (59%), followed by upland (27%) and rice paddy (9%) fields. Potato, radish, soybean and cabbage are the major upland crops (yellow-colored area), covering about 27% of the total upland area. Black circles indicate the locations of automatic weather stations

The Haean catchment has a geographical importance as one of the upper regions of the Soyang River Dam, which is used as the major drinking water source of urban residents (NIER 2012). Upland fields are intensively managed at high altitude (≥ 400 m a.s.l) with high application rates of N fertilizer (430 - 640 kg N ha^{-1} yr^{-1}), which have a high potential for significant rates of nutrient loading from upland fields to downstream in particular at heavy rainfall events. The Mandae stream forms the hydrological outlet of the Haean catchment located at 5 - 20° (average 11°) slopes and flows into the Soyang River Dam (Lee et al. 2011). 4-year average of measured total nitrogen (TN), total phosphorus (TP) and suspended solids (SS) in the Mandae stream water during rain events were 3.49, 0.75 and 924 mg l^{-1} (Eum 2015), respectively, which were beyond the final stage of water quality standard for inland water in South Korea (≤ 1.5, 0.15 and 15 mg l^{-1} for TN, TP and SS) (ME 2000). The climate of Haean catchment is characterized as the East Asian monsoon with 13-year (1999 - 2011) annual average air temperature of 8.7°C and annual precipitation of 1617 mm. About 70% of the annual precipitation is concentrated on the monsoon season (end June - August).

1.2.2 Description and application of the LandscapeDNDC model

The LandscapeDNDC is a process-based biogeochemical model, which integrates the Agriculture-DNDC (Abdalla et al. 2009; Giltrap et al. 2010; Li et al. 1992) and the Forest-DNDC (Jungkunst et al. 2012; Kiese et al. 2011; Li et al. 2000) for simulation of plant growth, C and N cycling, biosphere-atmosphere exchange of GHGs (e.g. CO_2, N_2O and CH_4) and nitrate leaching based on the interactions of plants, microbes and physico-chemical soil processes. The LandscapeDNDC is applicable for site scale as well as for regional, national and global scale simulations of arable, forest and grassland ecosystems (Cameron et al. 2013a; Haas et al. 2013; Kim et al. 2014; Werner et al. 2012). The model runs at a sub-daily time step requiring specific input data such as climate (e.g. air temperature, precipitation, radiation), soil properties (e.g. pH, bulk density, texture, SOC) and agricultural management practices (e.g. planting and harvesting dates, fertilizer types and rates, tilling date and depth). In this thesis, the LandscapeDNDC model was i) adopted and tested against field data of forest and upland crops under consideration of different application rates of N fertilizer and ii) in a coupled GIS-modelling approach applied for regional scale simulations of major upland crops and broadleaved trees in the Haean catchment.

Study 1: Application to the site scale simulation of radish cultivation under plastic mulch

All field measurements used for the model validation were carried out within the scheme of the TERRECO project (GRK 1565/1) in 2009 and 2010. 187 kg N ha^{-1} of inorganic fertilizer and 228 kg N ha^{-1} of organic fertilizer were manually applied to the entire field as a basal fertilization two weeks before radish seeding. In general, additional fertilizer is recommended to be applied around 20 days after seeding (RDA 2002a). In this study, additional fertilizer was applied one day after basal fertilization, which corresponded to 13 days before seeding. One day after basal fertilization the entire field was divided into four subplots and four different treatments of inorganic N fertilization (50, 150, 250 and 350 kg N ha^{-1}) were added to each subplot (49 m^2) in 4 replicates. All subplots were plowed at 15 - 20 cm depth one week after additional fertilization for creating rows and interrows. Rows were covered with black plastic mulch before seeding and 2 or 3 radish seeds were sown per plant hole on rows. Plastic mulch has continuously covered the rows until harvest.

Soil samples were taken from top to 60 cm soil depth and analyzed for pH, BD, texture, SOC and stone fraction. To measure the soil temperature and water content at 15 and 30 cm soil depth under plastic mulch, ECH_2O loggers (EM50 Data logger, Decagon Devices, WA, USA) were installed in all N fertilizer treatments with 2 replicates and recorded every 30 minutes. N_2O fluxes were measured in rows and interrows of 50, 150, 250 and 350 kg N treatments with 3 replicates by closed chamber method in connection with a photo-acoustic infrared trace gas analyzer (Multigas Monitor 1312, INNOVA, Ballerup, Denmark) (Berger et al. 2013b). Suction lysimeters connected with a soil hydrological monitoring network of standard tensiometers were installed at 15 cm depth in row and 30 cm depth in interrow across all N fertilizer treatments in order to quantify the nitrate concentration in seepage water on a weekly basis (Kettering et al. 2013). Above- and belowground radish biomass were measured in each N fertilizer treatment plot (dry weight of 8 radish per plot) at 25, 50 and 75 days after seeding. The meteorological data such as average, maximum and minimum air temperature, precipitation, radiation, relative humidity and wind speed was collected from the automatic weather station on site.

Still, the LandscapeDNDC is a one-dimensional model, which is not able to simulate lateral water and matter flow and, thus required to simulate row and interrow conditions separately. Meteorological input data of air temperature and precipitation was adjusted to consider the impacts of plastic mulch on soil environmental conditions. 90% of daily maximum air temperature and a half of daily precipitation, which was based on the field measurement at study site that 50% surface runoff from rainfall was mainly induced by plastic mulch (Arnhold et al. 2013), were used for the simulation conditions of row under plastic mulch. These findings were also supported by a previous field study of Tian et al. (2003), indicating 53% runoff from precipitation caused by plastic mulch (0.22 m height and 0.3 m width of row; 0.2 m height and 0.35 m width of row in this study). Adjusted meteorological data was only applied to the period when the row was covered with plastic mulch (before seeding to harvest) and the actual weather data was used for the rest of periods and the simulation of interrow conditions. For all LandscapeDNDC simulations a spin up period of 2 years was used considering the management input data of the 50 kg N treatment.

Study 2: Application to the regional scale simulation of major upland crop fields and temperate deciduous forest and assessment of mitigation options

This study was conducted in two parts: further site scale LandscapeDNDC model validation and regionalization. Except radish (Study 1) the model was initialized and validated against other major upland crops (i.e. potato, soybean and cabbage) and temperate deciduous forest sites dominated by

Quercus Mongolica of the Haean catchment. Detailed information on soil properties (e.g. pH, BD, SOC and texture) and agricultural management practices (e.g. seeding/harvest date, fertilization rate and tilling depth) were collected for each simulated crop field. The latter data was based on the intensive interviews with local farmers, who actually conducted all farming practices on sites. Daily meteorological data was provided from nearby weather stations. ECH_2O loggers (EM50 Data logger, Decagon Devices, WA, USA) were installed in each row and interrow in order to measure soil temperature and water content at 5 cm depth every 30 minutes. Using the closed chamber method in connection with a photo-acoustic infrared trace gas analyzer (Multigas Monitor 1312, INNOVA, Ballerup, Denmark) (Berger et al. 2013b), N_2O fluxes were measured in row and interrow with 3 replicates from May 16th to September 13th, 2011. Since there was no N_2O flux measurement in potato and cabbage fields, this data was provided from sites (Seo et al. 2013), which had similar soil and weather conditions to the ones in the Haean catchment. N_2O fluxes were measured only in row of cabbage and potato fields without plastic mulch by the closed chamber method every 2 or 3 times a week with 3 replicates from 2009 to 2012. Data on soil temperature and water content in cabbage and potato fields were not available. Field measurements of above- and belowground cabbage, potato and soybean biomass (5 - 8 plants per plot) were conducted in the Haean catchment within the scheme of the TERRECO project in 2009.

To implement the catchment scale simulation, a GIS database holding all site specific climate, soil and management information was established and linked to the LandscapeDNDC. A 2-year (2009 and 2010) land use map (ArcGIS 10.0) was created on the basis of an extensive field survey conducted within the framework of the TERRECO project. Taking into account the upland farming as the major agriculture of the Haean catchment, four major upland crops, accounting for half of the total upland area (Yanggu-gun 2011; 2012), were selected and applied for simulation of the LandscapeDNDC. The forest simulation was conducted with *Quercus Mongolica,* which is observed as the dominant tree species of the deciduous forest (Jung et al. 2014), on assumption that it covers the entire deciduous forest area of the Haean catchment. The field-based soil survey was carried out together with the land use survey in 2010 and the soil map was created using a 30 m resolution DEM. Since the soil map was made for indicating soil information on most typical land uses (e.g. major upland crop, forest and rice paddy fields) of the Haean catchment, other land uses were not considered in this map. Although averaged soil conditions of forest and upland crop types were well described in this soil map, it was somehow limited to be used for simulation of the LandscapeDNDC with the spatially explicit land use map, which considered 2-years of crop rotations at different location. Therefore, it was necessary to assume that specific soil conditions attributed to each upland crop type did not vary depending on location and topography. Similarly, forest soils were classified according to moderate (664 - 546 m a.s.l) and low ($\leq$ 545 m a.s.l) slopes and soils at the same slope were assumed to have the same soil conditions and N deposition (Kim et al. 2015, under review). Soil data on major upland crops and forest was taken from the soil map and applied to each upland crop and forest site based on the spatial explicit land use map. Input data on agricultural management practices was provided from the survey of 300 local farmers in 2010 (Shope et al. 2014). Data on application rates of N fertilizer was not collected from the survey and the official statistics, which were based on the intensive field survey conducted by the agricultural technology center located at each city/ county (RDA 2010; 2011), were used in the regionalization study. Meteorological data was collected from 12 automatic weather stations at different locations (450 - 1050 m a.s.l) within the Haean catchment. The locations of all weather stations were marked on the map (See Figure 1.1) and each weather station was linked to the nearest polygon (land use map) using ArcGIS analysis tool. Based on available information from RDA guidelines (2001; 2002a; b; 2003), the main parameters such as MaxTDD, Tlimit, OptYield and WUECMAX for potato, radish, soybean and cabbage were set for the simulation of plant growth dynamics of LandscapeDNDC.

To evaluate the mitigation potential for N_2O emission and nitrate leaching without penalizing crop yields, the decrease of N fertilization rates as well as split fertilizer applications were considered and benefits were tested against the conventional farming practices. Other farming practices such as seeding/ harvest date and tilling date and depth remained the same as conventional farming practices. Reduction rate of 1 - 75% and split fertilization into 2 or 3 times were randomly assigned (899 model runs) as management practices of each upland crop and applied to simulation of the LandscapeDNDC. The model ran for 4 years and the first 2 years with conventional farming practices were used as spin-up periods.

1.3 Results and discussion

Study 1: Site scale simulation of radish cultivation under plastic mulch

Application of the adjusted meteorological data of 90% maximum air temperature and 50% precipitation significantly improved the LandscapeDNDC prediction of soil temperature and water content under plastic mulch as compared to application of the actual weather data. Simulation of soil temperature for all N fertilizer treatments using 90% maximum temperature were in agreement with measurement values (90% max: $r^2 = 0.27 - 0.50$; actual weather: $r^2 \leq 0.19$). Studies of Nishimura et al. (2012) and Wang et al. (2009a) showed the dynamic patterns of soil temperature under plastic mulch, which temperature differences ranged between 5 and 10°C with the high soil temperature at early growing stage. In contrast with previous studies, slight variation of daily soil temperature was observed under plastic mulch during the entire measurement period in this study with average values of 23.9±1.2 and 23.2±0.9°C (simulation:

23.3±1.3 and 22.4±1.0°C) at 15 and 30 cm soil depth, respectively. According to drying and rewetting events during the growing season, the high dynamics of soil water content were observed and captured well by the LandscapeDNDC across all N fertilizer treatments. Soil water content was slightly higher at 30 cm depth with the wide range of 22.0 - 27.7 vol % than at 15 cm depth, ranging from 17.9 - 19.3 vol %. Since previous studies have shown that plastic mulch retained soil water by preventing soil evaporation (Ramakrishna et al. 2006; Xie et al. 2005) and the high soil water content of 53 - 64 vol % was observed under plastic mulch during the summer season (Nishimura et al. 2012), measured and simulated soil water content did not exceed 35 vol % during the monsoon season due to the high sand content (> 80%) of topsoil at this study site.

The LanscapeDNDC can distingush the simualtion between above- and belowground biomass. The aboveground biomass consists of leaves and stems and the belowground biomass inlcudes fine roots and coarse roots. At the day of harvest (75 days after seeding), the model overestimated the aboveground biomass for all N fertilizer treatments by 16%. In contrst, the belowground biomass was silghtly overestiamted only for 150 kg N treatment and underestimated for the rest treatments. The simulation of total biomass was in good agreement with the measurement (r^2 = 0.81 - 0.88), ranging between 4.4 - 5.6 and 4.0 - 5.4 t DW ha^{-1} for simulation and measurement, respectivley. NUE was calcualted as the ratio between simulated crop N uptake and the amount of applied N fertilizer. Meausred and simulated radish biomass increased with increasing N fertilization rates, whereas NUE decreased from 42.6 to 32.7% with higher application rates of N fertilizer. This result agreed with the study of Li et al. (2007), showing NUE substantially decreased from 75 to 18% with increasing N fertilziation rates from 200 to 800 kg N ha^{-1}. In additon, as compared to significantly increase in N fertilization rates from 50 to 350 kg N ha^{-1} (including basal fertilization: 465 - 765 kg N ha^{-1}), slightly increase in radish yields was observed (0.5 - 1.4 t DW ha^{-1} yr^{-1}) in this study. These findings were in good agreement with a small increase of 0.5 - 2.1 t DW ha^{-1} yr^{-1} from increasing N fertilization rates of 270 - 850 kg N ha^{-1} yr^{-1} reported by Liu et al. (2012). This was also supported by Ju et al. (2009) and Min et al. (2012b) who found that high fertilization rates (550 - 1100 kg N ha^{-1} yr^{-1}) did not substaintally enhance crop yields, whereas led to the twofold increase in N loss.

Elevated N_2O emissions were observed and simulated 3 days after N fertilizer application, followed by a steady decrease in N_2O emissions 2 - 3 months after fertilization. Measured and simulated N_2O emissions in rows showed slight increases with increasing rates of N fertilization. The LandscapeDNDC predicted peak N_2O emission (> 90 µg N m^{-2} h^{-1} in rows; > 50 µg N m^{-2} h^{-1} in interrows) about 17 days after additional fertilization, which were lower than measured N_2O emission in rows and interrows for all N fertilizer treatments. However, field measurements showed high uncertainty by varying in the range of

43.7 - 127.2 μg N m^{-2} h^{-1}. Measured and simulated mean N_2O emissions in rows during the period when the field measurement was conducted ranged between 27.9 - 65.8 and 51.8 - 63.1 μg N m^{-2} h^{-1}, respectively. Except for 50 (measurement) and 350 (simulation) kg N treatments, measured and simulated mean N_2O emissions in interrows showed similar emission levels among different N treatments, ranging between 26.6 - 29.9 and 54.5 - 56.6 μg N m^{-2} h^{-1}, respectively. Taking into account the high uncertainty and the low sampling frequency, the model captured well the temporal patterns of N_2O emissions in rows and interrows with r^2 up to 0.45 and $RMSPE_n$ of 0.81 - 1.41. Since the row was covered with plastic mulch just after N fertilizer application, higher N_2O emissions were assumed for row than interrow conditions. This hypothesis was confirmed by the field measurement, indicating approximately 2 times higher N_2O emissions from row than interrow. The LandscapeDNDC simulation of higher N_2O emissions in row as compared to interrow until 30 days after fertilization proved this hypothesis as well, even though the model predicted higher N_2O emissions only in 250 kg N treatment with respect to the same period of measurement data. These results were partially supported by Nishimura et al. (2012), reporting plastic mulch could enhance N_2O emission through denitrification process due to the high N content and the low O_2 concentration under plastic mulch. In this study, N_2O emissions could mainly be induced by nitrification rather than denitrification. Very high sand content (> 80%) of topsoil could still allow substantial aeration via the plant hole in plastic mulch, indicating no substantial differences of N_2O emissions between row and interrow. These findings were supported by the LandscapeDNDC simulation of the rather low annual mean anaerobic volume fraction (> 18%) in topsoil. The annual direct N_2O emissions for all N fertilizer treatments were calculated from the daily simulations of the LandscapeDNDC. Direct N_2O emissions in row and interrow increased with increaing N fertilization rates, ranging between 2.1 - 2.4 and 2.4 - 3.2 kg N ha^{-1} yr^{-1}, respectively. N_2O EF_d was calcualted by the difference of N_2O emissions between fertilized and unfertilized fields devided by the applied N fertilizer. N_2O EF_d showed higher value in interrow as compared to row in the range of 0.26 - 0.36%. N_2O EF_d for row and interrow were somehow within the uncertainty range of IPCC N_2O EF_d (0.3 - 3.0%), whereas much lower than the default value of 1% (IPCC 2006). The low N_2O EF_d for radish in this study were supported by Xiong et al. (2006), indicating a comparable N_2O EF_d of 0.39% for radish under similar management and soil conditions. This result showed a high potential of LandscapeDNDC application for improving predictions of N_2O emission as well as development of national N_2O EF_d. Simulated nitrate leaching rates were multiplied by IPCC EF_5 of 0.0075 (IPCC 2006) to estimate indirect N_2O emission. Indirect N_2O emissions (2.0 - 3.4 kg N ha^{-1} yr^{-1}) were in the same range of direct N_2O emissions, which indicated their significance under the given soil and weather conditions of this study site.

Field measurement of nitrate concentrations in soil water at 15 cm depth of row and 30 cm depth of interrow was compared with the LandscapeDNDC simualtion. Nitrate concentrations in soil water were calcualted with predicted amount of water and nitrate in given soil layers. High rates of N fertilizer generally increased measured and simulate nitrate concentrations. The peak nitrate concentration in row and interrow of all N treatment plots (> 200 mg NO_3-N l^{-1}) was observed and simulated about 30 - 39 days after additional fertilization and gradually decreased to a low level of 10 mg NO_3-N l^{-1} afterwards. Measured nitrate concentrations were higher in row than interrow, which were captured well by the simulation of LandscapeDNDC with r^2 up to 0.89 and $RMSPE_n$ of 0.75 - 1.79. Measured and simulated mean nitrate concentrations in row and interrow during the period of field measurement ranged between 79.8 - 143.2 and 53.0 - 108.0 mg NO_3-N l^{-1} in measurement and 95.5 - 172.1 and 91.1 - 124.7 mg NO_3-N l^{-1} in simulation, respectively. The annual nitrate leaching rate below radish root zone was calcualted by daily simulations of the LandscapeDNDC for all N fertilizer treatments. High nitrate leaching rates were simulated both in row and interrow of all N treatments. Interrow revealed higher nitrate leaching rate of > 400 kg N ha^{-1} yr^{-1} than row (< 300 kg N ha^{-1} yr^{-1}) due to approximately 1.8 times higher percolation rate and no N uptake by the radish crop (> 190 kg N ha^{-1} yr^{-1}) in interrow. These findings proved the hypothesis of less nitrate leaching rate under plastic mulch than no-mulch in this study, which was also supported by Romict et al. (2003) and Zhang et al. (2012), showing reduced nitrate leaching rate by 11 and 62% under plastic mulch as compared to no-mulch, respectively. It should be noted that the previous studies showed comparable nitrate leaching rates in the range of 277 - 354 kg N ha^{-1} yr^{-1} from intensively managed crop fields (Min et al. 2012b; Song et al. 2009; Zhao et al. 2010), which were mainly caused by 20 - 30% of applied N fertilizer in contrast with 59% of applied N in this study. These findings emphasized that the reduction of nitrate leaching should be considered as the highest priority in the further N management at our study site.

Study 2: Regional scale simulation of major upland crop fields and temperate deciduous forest and assessment of mitigation options

2.1 Site scale simulation of potato, cabbage and soybean fields

In the first study (Chapter 3), soil temperature and water content under plastic mulched radish field were well captured by the LandscapeDNDC with adjusted meteorological data of 90% maximum air temperature and a half of precipitation. Based on this adaptation, the LandscapeDNDC simulated soil temperature and water content at 5 cm depth in the soybean field. In contrast to the first study, field measured data on soil temperature and water content in interrow was also available and compared with simulated values in this study. The model successfully captured the temporal dynamics of soil temperature in row with 90% maximum air temperature and interrow with the actual average air temperature with r^2 up to 0.67 and 0.76 and ME of 0.66 and 0.30, respectively. Measured and simulated mean soil temperature in row was 22.0±2.6 and 22.2±2.3°C, respectively, while observed soil temperature in interrow was slightly underestimated by 7%. Comparison of measured mean soil temperature between row and interrow revealed slightly higher soil temperature in row with a value of 0.5°C (max: 0.9°C; min: 0.4°C). This result agreed well with Lie et al. (2004a), showing 0.6°C higher mean soil temperature at 5 cm depth in row under plastic mulch during the wheat growing season. A small difference of max and min soil temperature between row and interrow was also reported by Chakraborty et al. (2010), indicating 1.5 and 0.4°C higher max and min soil temperature at 5 cm depth in row under plastic mulch as compared to interrow under bare soil. In contrast to soil temperature, soil water content showed significant difference between row and interrow. The soil water content was much lower in row as compared to interrow with the range of 2 - 19 vol %. A wide range of soil water content in interrow was observed, ranging from 15 to 50 vol %. The LandscapeDNDC captured well drying and rewetting events at 5 cm soil depth in row and interrow during the soybean growing period. Measured and simulated mean soil water content in row was 9.0±4.9 and 12.5±6.5 vol %, respectively and higher soil water content was predicted in interrow (17.8±8.0 vol %) as well as the field measured values (30.2±10.8 vol %). Measured soil water content in row was significantly lower at the beginning and the end of growing season (< 10 vol %) and the overall soil water content was < 20 vol %. The LandscapeDNDC also predicted the low soil water content for the same period, but still overestimated the measured values. Taking also into account the high uncertainty of field measurements due to no replication, soil water content was relatively well captured by the LandscapeDNDC model (row: r^2 = 0.61, ME = -0.16, $RMSPE_n$ = 1.08; interrow: r^2 = 0.19, ME = -1.23, $RMSPE_n$ = 1.49). Previous studies have reported that evaporation is lower under plastic mulch than no-mulch due to the restriction of soil water by plastic mulch (Anikwe et al. 2007; Xie et al. 2005; Zhao et al. 2012). These findings agreed with the simulation result of the LandscapeDNDC, showing higher evaporation of 481 mm in interrow than that of 304 mm in row during the period of field measurement.

It was already identified in the first study (Chapter 3) that the LandscapeDNDC could differentiate the simulations of above- and belowground biomass. Potato, soybean and cabbage biomass were separately simulated and compared with available field measured values. Measured total biomass (sum of above- and belowground biomass) of potato, soybean and cabbage were 11.3, 5.8 and 9.7 t DW ha^{-1} at the day of harvest, which were successfully captured by the LandscapeDNDC with the simulated total biomass of 11.3, 5.6 and 9.6 t DW ha^{-1}, respectively (r^2 = 0.84 - 0.98). Measured and simulated biomass increased with increasing N fertilization rates, whereas NUE decreased by 51.4%. Among the upland crops, potato showed the highest yield both for measurements and simulations with the lowest NUE, which agreed well with the findings of Zvomuya and Rosen (2002), reporting 11.6 t DW ha^{-1} with the low NUE (38.2%) in a comparable fertilized potato field (336 kg N ha^{-1}).

4 year-field measurements of N_2O emissions in cabbage and potato fields (Chuncheon-si) and 1-year measurements in soybean field (Haean catchment) were used for further site scale validation of the LandscapeDNDC. Rows in cabbage, potato and soybean fields were covered with black plastic mulch before transplanting/ seeding and were removed from the first two-crop fields while N_2O emission were measured. N_2O emissions varied over the entire measurement period. The high peak of N_2O emission in cabbage and potato fields was observed around 10 days following the application of N fertilizer. Due to higher fertilization of cabbage, about 2 times higher N_2O emissions were measured in cabbage field as compared to the potato field. There was no fertilizer applied to the soybean field and the first N_2O emission peak was observed about 6 days after seeding in row and interrow following a rainfall event. In general, the LandscapeDNDC captured the seasonal dynamics of N_2O emission and the fertilizer induced peak emission. Comparison between measured and simulated mean N_2O emissions revealed the underestimation of the LandscapeDNDC by 6.4% for cabbage field (r^2 = 0.21; ME = 0.11; $RMSPE_n$ = 0.94; p < 0.001) and by 19.9% for potato field (r^2 = 0.31; ME = 0.21; $RMSPE_n$ = 0.89; p < 0.001). Measured and simulated 4-year mean N_2O emissions were 58.0±80.4 and 54.3±62.2 μg N m^{-2} h^{-1} in cabbage field and 27.1±27.6 and 21.7±22.1 μg N m^{-2} h^{-1} in potato field, respectively. The field measurement and the LandscapeDNDC simulation showed about 2 times higher N_2O emissions in interrow as compared to row under plastic mulch in soybean field. Measured mean N_2O emissions in row and interrow were 16.5±24.3 and 34.7± 46.1 μg N m^{-2} h^{-1}, respectively. The LandscapeDNDC predicted the temporal patterns of N_2O emissions in row and interrow well, however, generally overestimated N_2O emissions (row 5.7±7.5 μg N m^{-2} h^{-1}; interrow 14.9±11.5 μg N m^{-2} h^{-1}). The annual N_2O emission calculated from daily simulations of the LandscapeDNDC ranged between 3.0 - 5.9 and 1.4 - 1.9 kg N ha^{-1} yr^{-1} for 4 years in cabbage and potato fields, respectively. These results were supported by the field studies of Cao et al. (2006) and Gao et al. (2013), reporting 5.0 and 1.5 kg N ha^{-1} yr^{-1} in cabbage and potato fields under comparable management and soil conditions, respectively. Simulated 4-year mean anaerobic volume faction of 15% in topsoil indicated that N_2O emissions in cabbage and potato fields were mainly produced through nitrification process. Due to double cropping with the high N fertilization rate (640 kg N ha^{-1} yr^{-1}), simulated nitrate leaching rate was much higher in cabbage field as compared to potato field, ranging between 202.9 - 398.0 and 51.7 - 63.0 kg N ha^{-1} yr^{-1} over 4 years, respectively. Consequently, indirect N_2O emission from simulated nitrate leaching was also higher in cabbage field

than potato field with 4-year mean values of 2.2 and 0.4 kg N ha^{-1} yr^{-1}, respectively. N_2O EF_d of cabbage and potato fields were 0.35% and 0.39%, respectively, which were within the uncertainty range of IPCC EF_d (0.3 - 3.0%), but lower than the default value of 1.0% (IPCC 2006). Predicted annual N_2O emissions from row and interrow of non-fertilized soybean field were 0.31 and 0.72 kg N ha^{-1} yr^{-1}, respectively, which were likely to be induced by residual N in soil (row 12.7 kg N ha^{-1}; interrow 21.5 kg N ha^{-1}) from the previous radish cultivation. However, supporting field measured data on initial soil N content before soybean cultivation was not available. Taking into account the annual N_2O emissions of 1.23 and 1.65 kg N ha^{-1} from non-fertilized soybean fields by MacKenzie et al. (1997) and Gregorich et al. (2008), simulated and measured annual N_2O emissions from soybean field in this study showed relatively low values. Previous studies have reported that nitrate leaching rate is decreased under plastic mulch (Nishimura et al. 2012; Romic et al. 2003; Zhang et al. 2012). These findings were supported by the LandscapeDNDC simulation for non-fertilized soybean field, showing significantly less nitrate leaching rate from row under plastic mulch (0.65 kg N ha^{-1} yr^{-1}) as compared to interrow under no-mulch (29.7 kg N ha^{-1} yr^{-1}). With respect to the higher nitrate leaching rate from interrow than row, indirect N_2O emission from simulated nitrate leaching was also higher in interrow (0.22 kg N ha^{-1} yr^{-1}).

2.2 Site scale simulation of three temperate deciduous forest sites

Estimated N deposition of three forest sties at high (38.14°N, 128.6°E, 950 m a.s.l), medium (38.18°N, 128.8°E, 650 m a.s.l) and low (38.17°N, 128.7°E, 450 m a.s.l) altitudes were 24±13.8, 31±2.14 and 51±15.3 kg N ha^{-1}, respectively (Berger et al. 2013a). Taking into account differences of N deposition among sites, the LandscapeDNDC simulated N_2O emission and soil temperature and water content and was validated against the measured values. N_2O uptake was observed at all three sites (from -0.28 to -16.3 μg N m^{-2} h^{-1}) by Berger et al. (2013a), which was beyond the current prediction capacity of the LandscapeDNDC and only emission values (> 0) were taken from measured data to compare with simulated N_2O emission.

Previous studies have shown no significant correlation between N deposition and N_2O emission from forest soils (Ambus and Robertson 2006; Pilegaard et al. 2006; Wei et al. 2008), which are in agreement with measured and simulated N_2O emissions from the temperate deciduous forest of the Haean catchment. Soil temperature and water content, which are major factors controlling soil N mineralization, production and consumption of N_2O emission (Aguilera et al. 2013; Brumme and Khanna 2009; Eickenscheidt and Brumme 2013; Luo et al. 2013; Stange et al. 2000), would be more significant for soil N_2O emissions in this study. Soil temperature showed the strong correlation with N_2O emissions at high altitude-site (mea r^2

= 0.41; sim r^2 = 0.54) and soil water content was more important factor for N_2O emissions at low (mea r^2 = 0.29; sim r^2 = 0.74) altitude-site. Both measured and simulated N_2O emissions from medium altitude-site showed the low or no correlation with soil temperature (mea r^2 = 0.18; sim r^2 < 0.1) and water content (mea and sim r^2 < 0.1). The dynamics of N_2O emissions derived from drying and rewetting events during the monsoon season were relatively well captured by the LandscapeDNDC. Due to the scarcity of measured N_2O emission data, however, the assessment of model performance was devalued. ME was below zero for all three sites and r^2 was ≤ 0.1 except for high altitude-site (r^2 = 0.46).

2.3 Regional simulation of crop yield, N_2O emission and nitrate leaching from the Haean catchment

The LandscapeDNDC simulation of major upland crop fields of the Haean catchment showed differences between year 2009 and 2010 (Figure 1.2). Estimated potato, radish, soybean and cabbage biomass were 17.8, 6.4, 6.3 and 11.0 t DW ha^{-1} in 2009 and slightly lower in 2010 with values of 14.8, 5.5, 5.8 and 11.0 t DW ha^{-1}, respectively (Table 1.1). Annual direct N_2O emissions increased with increasing rates of applied N fertilizer. Predicted annual mean direct N_2O emission from upland crops was 2.14 kg N ha^{-1} in 2010, which was slightly higher as compared to 1.92 kg N ha^{-1} in 2009. The highest N_2O emission was predicted for radish, followed by potato, cabbage and soybean cultivation, ranging from 1.17 to 2.77 kg N ha^{-1} in 2009. Similarly, radish showed the highest N_2O emission also in 2010, followed by cabbage, potato and soybean in the range of 1.29 - 2.77 kg N ha^{-1}, respectively. N_2O EF_d was calculated by difference between simulated fertilizer- and non-fertilizer-induced N_2O emissions divided by applied total N fertilization rate. N_2O EF_d ranged between 0.54 - 1.09% in 2009 and 0.59 - 1.22% in 2010, which is in the uncertainty range of IPCC EF_d (0.3 - 3%) (IPCC 2006). The mean EF_d for total upland fields of the Haean catchment was slightly lower than the IPCC default value of 1% (IPCC 2006) with values of 0.80 and 0.94% in 2009 and 2010, respectively. Similar to N_2O emission, simulated annual nitrate leaching rates generally increased with increasing N fertilization rates. The model predicted the highest nitrate leaching rate from cabbage cultivation in 2009 but from radish cultivation in 2010. The annual nitrate leaching rates from the total upland fields of the Haean catchment ranged between 74.7 - 135.0 and 70.4 - 151.4 kg N ha^{-1} with the annual mean values of 112.6 and 125.4 kg N ha^{-1} in 2009 and 2010, respectively (Figure 1.2). Taking into account approximately 53% and 60% of applied N fertilizer lost by nitrate leaching in 2009 and 2010, respectively, the hypothesis of this study was confirmed that nitrate leaching was the dominant pathway of N loss from the total upland fields of the Haean catchment. Indirect N_2O emission from simulated nitrate leaching was estimated by using the IPCC EF_5 of 0.0075 (IPCC 2006). Due to the overall high nitrate leaching rate, estimated indirect N_2O emission revealed the similar range of direct N_2O emission. Indirect N_2O emissions from the total upland fields ranged between 0.56 - 1.01

and 0.53 - 1.14 kg N ha^{-1} in 2009 and 2010, respectively. The total N_2O emission (sum of direct and indirect N_2O emissions) from the entire upland fields of the Haean catchment were 2.76 and 3.08 kg N ha^{-1} in 2009 and 2010, respectively. The highest total N_2O emission was expected from radish field, followed by cabbage, potato and soybean fields through 2009 - 2010.

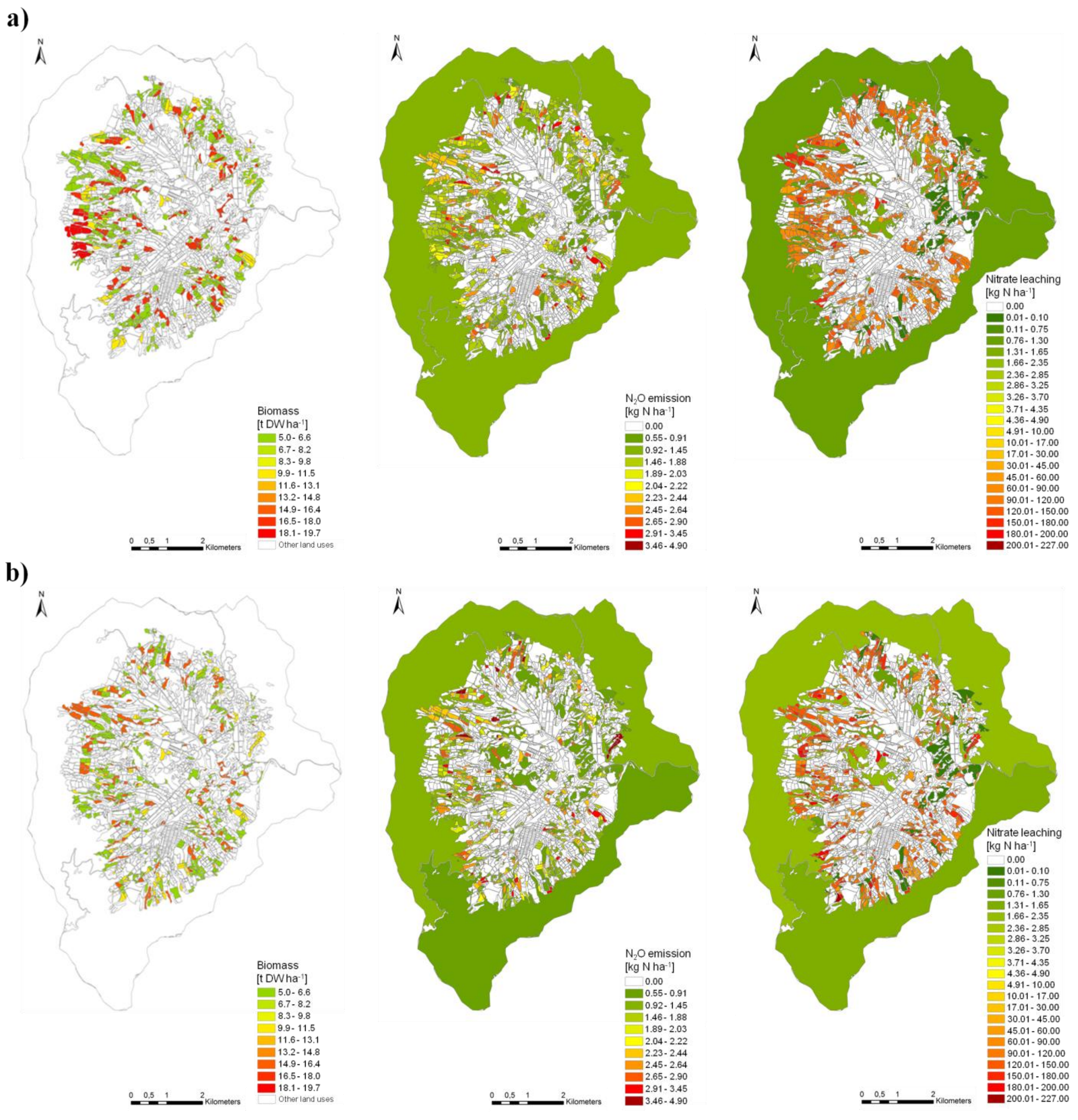

Figure 1.2 Regional distribution of simulated annual crop biomass, N_2O emission and nitrate leaching from the Haean catchment in a) 2009 and b) 2010

In contrast to the upland fields, estimated annual mean direct N_2O emissions from the temperate deciduous forest were similar between 2009 and 2010 with values of 0.51 and 0.50 kg N ha^{-1}, respectively (Table 1.1). Regression analysis showed the strong correlation between N_2O emission and soil temperature with r^2 up to 0.87 and 0.88 in 2009 and 2010, respectively, while no significant effect was found with variation of soil water content ($r^2 \leq 0.1$). Estimated N_2O emission derived from N deposition was in the range of 1.9 - 9.3%, which showed the similar range of 6 - 13% found for temperate forest (Eickenscheidt et al. 2011) and 8 - 10% reported for subtropical forest ecosystems (Zhu et al. 2013). Simulated annual mean nitrate leaching rates from the deciduous forest was 0.001 and 0.004 kg N ha^{-1} in 2009 and 2010, respectively (Table 1.1). No significant correlation was found between nitrate leaching rate and soil water content ($r^2 < 0.1$). Due to very low leaching rate, indirect N_2O emission from simulated nitrate leaching rate had hardly impact on the total N_2O emissions (sum of direct and indirect N_2O emissions).

Table 1.1 The LandscapeDNDC simulation of N_2O emission, nitrate leaching rate and biomass production of the Haean catchment in 2009 and 2010

Land use	Crop/Slope	Year	N_2O emission [kg N ha^{-1}] Direct	Indirect[a]	Total[b]	NO_3^- leaching [kg N ha^{-1}]	N_2O EF_d [%][c]	Biomass [t DW ha^{-1}]
Upland	Potato	2009	1.87	0.84	2.71	111.6	0.54	17.8
		2010	1.92	0.97	2.89	129.2	0.59	14.8
	Radish	2009	2.78	0.96	3.74	127.3	0.95	6.4
		2010	2.77	1.14	3.91	151.4	1.03	5.5
	Soybean	2009	1.17	0.56	1.73	74.7	1.09	6.3
		2010	1.29	0.53	1.82	70.4	1.22	5.8
	Cabbage	2009	1.85	1.01	2.86	135.0	0.61	11.0
		2010	2.59	1.13	3.72	150.5	0.93	11.0
Forest	Moderate	2009	0.62	0.00	0.62	0.00		
		2010	0.60	0.00	0.60	0.01		
	Low	2009	0.40	0.00	0.40	0.00		
		2010	0.39	0.00	0.39	0.00		

[a] N_2O emission from simulated nitrate leaching. Indirect N_2O emission was calculated using the IPCC default value of 0.0075 (IPCC 2006)

[b] Sum of direct and indirect N_2O emissions

[c] Direct N_2O emission factor [%] = {(N_2O emission from fertilized upland field - N_2O emission from unfertilized upland field) / applied total N fertilizer} * 100

The reduction of N_2O emission and nitrate leaching from the Haean catchment inform 2009 to 2010 could mainly be explained by the decrease in cultivation area (-23%) and related amount of N fertilization (-

28%) as compared to 2009. The area-weighted total N_2O emission from the Haean catchment was about 3.31 and 2.93 t N yr^{-1} in 2009 and 2010, respectively. Even though the temperate deciduous forest covers approximately 59% of the total area of the Haean catchment, still more than 50% of the total N_2O emission was derived from the fertilized upland fields (27% of the catchment area) through 2009 - 2010. The area-weighted nitrate leaching rate of the Haean catchment was 72.0 and 59.5 t N yr^{-1} in 2009 and 2010, respectively, with almost the entire nitrate leaching being induced from the upland crop cultivation and hardly contribution from the temperate deciduous forest (< 0.01 t N yr^{-1}). The total nitrate leaching as calculated from the simulation of the major upland crops of the Haean catchment was in the similar range of NO_3-N loadings (calculated from discharge and NO_3-N concentration measurements) in the Mandae stream with the cumulative values of 89.9 and 81.5 t N yr^{-1} in 2009 and 2010 (Eum 2015), respectively. Overall, estimated total N loss from 4345 and 4197 ha of the Haean catchment was 101.7 and 87.7 t N yr^{-1} in 2009 and 2010, respectively. Nitrate leaching was shown as the most significant pathway of N loss, contributing approximately 80% of the total N loss (sum of N_2O, NO_3, NO, NH_3, NH_4 and N_2) from the Haean catchment in 2009 and 2010.

2.4 Assessment of mitigation options for N_2O emission and nitrate leaching from upland crop cultivation in the Haean catchment

It is common that farmers apply more N fertilizer than the actual crop N demand (Snyder et al. 2014), which may result in substantial N_2O emission and nitrate leaching from surplus N in soil. Decrease in excessive N addition and surplus N in soil could be the most effective mitigation option in agriculture (Hoben et al. 2011). However, mitigation options which reduce GHG emission and increase/ sustain crop yield simultaneously are more likely to be chosen rather than only aiming to reduce emissions (Smith et al. 2008). The study of Sehy et al. (2003) showed the reduction of fertilization rate from 150 to 125 kg N ha^{-1} resulted in 34% less N_2O emission without affecting maize yield. Liu et al. (2012) also demonstrated the decrease in fertilization rate from 430 to 270 kg N ha^{-1} led to reduction of N_2O emission by 26% with maintaining the current crop yield. In this study, reduction in N fertilization rates and splitting fertilizer application was tested as mitigation options for N_2O emission and nitrate leaching from upland fields of the Haean catchment. Adopted mitigation options were based on the maximum reduction of N_2O emission and nitrate leaching, while ensuring the same crop yield as conventional farming practices. Overall, splitting fertilizer application into 3 times (Split3) showed slightly higher mitigation potential for N_2O emission and nitrate leaching. This was mainly caused by the overall higher reduction of total fertilization rates with Split3 (35%) compared to the Split2 (33%). Figure 1.3 shows the regional distribution of N loss (N_2O emission and nitrate leaching rate) from farmers` practices and mitigated N loss by Split3 in 2009 and 2010. Due to the slightly higher mitigation potential for N loss by Split3 rather than Split2, here the reduction rate by Split3 was only presented. The range of reduced fertilization rate was 16 - 209 and 49 - 194 kg N ha^{-1} in 2009 and 2010, respectively. As compared to the farmers` practices, simulated annual N_2O emissions were expected to decrease by 45 and 43% in 2009 and 2010, respectively with the application of Split3. By Split2, about 34 and 39% of N_2O emissions decreased in 2009 and 2010, respectively. Expected reduction rate of simulated annual nitrate leaching was 38 and 37% by Split3 and Split2 in 2009, respectively. In 2010, significantly more reduced nitrate leaching was predicted by 49 (Split3) and 48% (Split2). Of the total upland fields, the highest N_2O emission was reduced in radish field by Split3, followed by cabbage, soybean and potato fields in the range of 0.30 - 2.14 kg N ha^{-1} in 2009. Different from 2009, the highest reduction rate of 1.91 kg N ha^{-1} was expected from cabbage field by Split2, but other crops showed more reduction of N_2O emissions by Split3, ranging from 0.44 to 1.72 kg N ha^{-1} in 2010. Simulated annual nitrate leaching rate was highly reduced from cabbage field in 2009 with Split2 and Split3 showing similar reduction rates of 94.3 and 94.2 kg N ha^{-1} yr^{-1}, respectively. The second largest reduction rate of simulated nitrate leaching was shown in radish field by Split3, followed by potato and soybean fields in the range of 19.2 - 77.1 kg N ha^{-1} yr^{-1}. In 2010, more reduced nitrate leaching rates were estimated in cabbage fields by Split3, followed by radish, potato and soybean fields, ranging from 22.0 to 136.4 kg N ha^{-1} yr^{-1}.

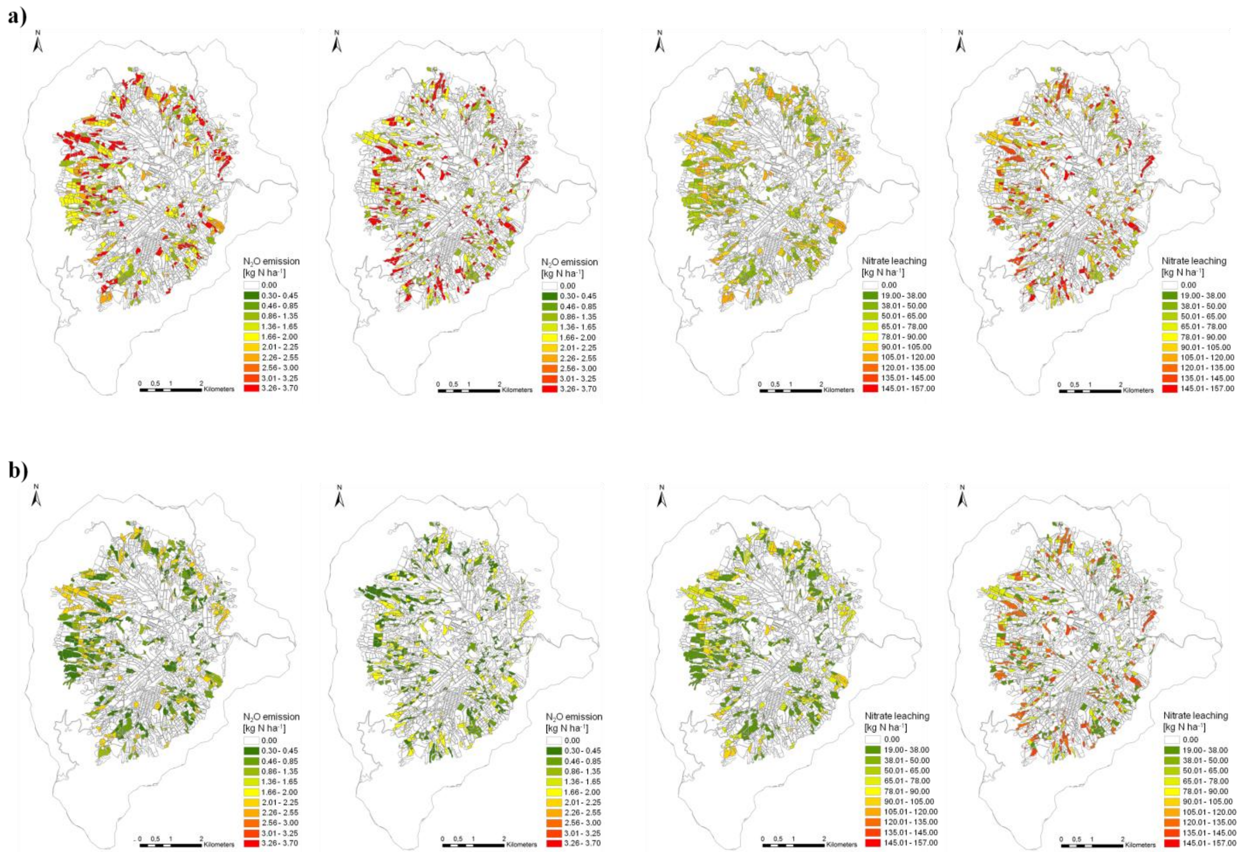

Figure 1.3 Comparison between a) N loss by farmers` practices and b) reduced N loss by mitigation option in 2009 and 2010. Note that only row with upland crops was simulated for assessing mitigation options and interrow and forest were not simulated

Splitting fertilizer application into 2 times (i.e. basal and additional fertilization) is a common farming practice for cabbage and radish cultivation in the Haean catchment. In general, additional fertilization has been conducted about 33 days after basal fertilization in cabbage and radish fields. Different from cabbage and radish cultivation, a single fertilization (i.e. only basal fertilization) is usual for potato and soybean cultivation under conventional farming practices (TERRECO, unpublished data). Simulation results of mitigation options showed that slightly earlier fertilization was beneficial to reduce N_2O emission and nitrate leaching in the cabbage field (12/16 instead of 33 days after basal fertilization) and the radish field (26/30 instead of 32 days after basal fertilization). The area-weighted N_2O emission and nitrate leaching rate with the application of Split2 and Split3 showed significantly reduced N loss from the Haean catchment (Table 1.2). Due to the decrease in cultivation area in 2010, reduction of N_2O emission and nitrate leaching was higher in 2010 as compared to 2009. By Split3, reduction potential for fertilizer-induced N_2O emission and nitrate leaching was 0.78 and 39.5 t N yr^{-1} in 2010, which were approximately 52 and 78% reduction rate from the conventional farming practices (Table 1.2). Application rate of N fertilizer could be reduced by 47 t N yr^{-1} in 2010. Similar range but less N_2O emission, nitrate leaching and N fertilization rate were estimated to decrease by Split2 as compared to Split3 through 2009 - 2010.

Taking into account nitrate leaching as the most significant pathway of N loss from the Haean catchment, Split3 would be better option for decreasing more nitrate leaching rate and N_2O emission as compared to Split2. However, considering the cost efficiency such as time and labor needed to conduct split applications, Split2 with reduced fertilization rates in combination with changes in application time, which also showed relatively high potential for reducing N loads to the environment, might be the most promising tool for management adoption accepted by farmers in the Haean catchment. In addition, differences of simulation results between 2009 and 2010 indicate the high spatial and temporal variabilities of reduced environmental N loads, which could be taken into account for further assessment of mitigation potentials guiding even spatial explicit adaptation of agricultural management in the Haean catchment.

Table 1.2 Mitigation potential for N_2O emission and nitrate leaching from upland fields of the Haean catchment in 2009 and 2010

Crop	Year	Option	Fertilization rate [t N yr^{-1}]	N_2O emission [t N yr^{-1}][a]	Nitrate leaching [t N yr^{-1}]
Potato	2009	Split3	-3.82 (7)	-0.11 (22)	-6.02 (56)
		Split2	-3.37 (6)	-0.12 (24)	-5.78 (54)
	2010	Split3	-11.8 (27)	-0.16 (38)	-12.3 (83)
		Split2	-11.5 (27)	-0.16 (38)	-12.5 (84)
Radish	2009	Split3	-16.3 (26)	-0.52 (61)	-14.8 (74)
		Split2	-13.4 (21)	-0.24 (29)	-11.5 (58)
	2010	Split3	-14.8 (38)	-0.32 (59)	-14.6 (84)
		Split2	-14.2 (36)	-0.25 (47)	-14.0 (80)
Soybean	2009	Split3	-5.26 (56)	-0.10 (48)	-2.66 (44)
		Split2	-5.53 (59)	-0.08 (38)	-2.39 (39)
	2010	Split3	-7.21 (74)	-0.10 (43)	-3.18 (43)
		Split2	-7.09 (72)	-0.10 (42)	-3.08 (41)
Cabbage	2009	Split3	-20.6 (60)	-0.19 (63)	-9.30 (82)
		Split2	-20.6 (60)	-0.20 (64)	-9.31 (82)
	2010	Split3	-13.4 (56)	-0.20 (64)	-9.45 (87)

Split2	-13.1 (55)	-0.20 (65)	-9.25 (85)

Note that negative values are difference between mitigation options and farmers` practices and values in brackets represent mitigation rates [%] by application of mitigation options

[a] Sum of direct and indirect N_2O emissions

1.4 Conclusions

The effects of intensive farming practices on N_2O emission, nitrate leaching and biomass production of the Haean catchment in South Korea were tested and analyzed by the LandscapeDNDC model in this thesis. The first study (Chapter 3) focused on adaptation of the LandscapeDNDC model for simulation of spatial difference in N_2O emission and nitrate leaching between row with plastic mulch and interrow without mulch with regard to four different N treatments of a radish field. In the second study (Chapter 4), the site application of the LandscapeDNDC was extended to other upland crops (i.e. cabbage, potato, radish and soybean) and temperate deciduous forest sites constituting the main land use types in the Haean catchment. After successful site validation the LandscapeDNDC model was used to upscale crop yields, N_2O emissions and nitrate leaching for the main land uses of the Haean catchment. Finally, mitigation options for N_2O emission and nitrate leaching without penalizing crop yields were evaluated to potentially guide improvement of farmers` practices in order to reduce N loads to the environment of the Haean catchment.

Study 1 Conclusions: Site scale simulation of radish cultivation under plastic mulch

The first study showed the successful application of the LandscapeDNDC model to the distinctive environmental conditions (e.g. monsoon season) and farming practices (e.g. plastic mulch, excessive N fertilizer use, sand dressing, etc) of the Haean catchment in South Korea. Taking account of different soil environmental conditions between plastic mulch and no-mulch by adjusting maximum air temperature and annual precipitation, the LandscapeDNDC simulation of N_2O emission, nitrate leaching, soil temperature and water content and radish biomass in response to 50, 150, 250 and 350 kg N ha^{-1} treatments agreed well with the measured values. Simulated nitrate leaching rate was revealed as the significant source of N loss from the radish field with the average value of 352 kg N ha^{-1} yr^{-1}. Due to this high nitrate leaching rate, estimated annual indirect N_2O emission was higher than the annual direct N_2O emission with the values of 2.6 and 2.4 kg N ha^{-1} yr^{-1}, respectively. Estimated total N_2O emission (sum of direct and indirect N_2O emissions) was 5 kg N ha^{-1} yr^{-1}. Both measured and simulated radish biomass demonstrated the necessity of improving farmers` practices of the Haean catchment due to no significant difference of radish biomass among four N treatments. Radish biomass slightly increased from 0.5 to 1.1 t

DW ha^{-1}, whereas increasing N fertilization rates by 3 to 7 times. This finding could be implemented to the further study, which is supplemented with more detailed scenarios for mitigating nitrate leaching rate and N_2O emission while optimizing the crop yield. It was a challenge to apply the plastic mulch into the LandscapeDNDC model due to its complicated effect on soil biogeochemical processes and the horizontal movement of nutrient and water between plastic mulched-row and no-mulched-interrow was hard to be considered in this study. The further research would be required to be connected with hydrological and thermal models for better prediction of the effects of plastic mulch on soil nutrient cycling and associated N_2O emission and nitrate leaching.

Study 2 Conclusions: Regional scale simulation of major upland crop fields and temperate deciduous forest and assessment of mitigation options

Taking into account different environmental conditions and agricultural managements, the LandscapeDNDC was successfully applied to the simulation of N_2O emission, nitrate leaching and crop yield from major upland crop fields and deciduous forest of the Haean catchment for two consecutive years 2009 and 2010. With respect to no significant difference of weather condition (air temperature 8.2 and 7.9°C; precipitation: 1527 and 1522 mm) between 2009 and 2010, about 23% reduction in cultivation area led to less N_2O emission, nitrate leaching rate crop production in 2010 as compared to 2009. Estimated total N_2O emissions (sum of agricultural and forest N_2O emissions) from the Haean catchment were 3.3 and 2.9 t N yr^{-1} in 2009 and 2010 with 52% of the total N_2O emissions originating from upland fields covering only 27% of the total catchment area. The LandscapeDNDC simulation of nitrate leaching was revealed as the most significant pathway of N loss from the Haean catchment. The total nitrate leaching rates from the Haean catchment were 72.0 and 59.5 t N yr^{-1} in 2009 and 2010, respectively. Thereby, 99% of the leaching was induced from the fertilized upland fields. These numbers agreed very well with NO_3-N loads calculated from discharge and concentration measurements at the catchment outlet with 89.9 and 81.5 t N yr^{-1} in 2009 and 2010. Overall, estimated total N losses from the Haean catchment were 101.7 and 87.7 t N yr^{-1} in 2009 and 2010, respectively. This study demonstrates that the use of the IPCC default N_2O EF_d of 1% would significantly overestimate direct N_2O emissions from the Haean catchment characterized by sandy soils and a monsoon climate. However, with nitrate leaching as the main fate of N fertilizer application indirect N_2O emissions from the Haean catchment are in the same range of direct N_2O emissions and thus, cannot be neglected.

Decrease in N fertilization rates with splitting fertilizer into 2 and 3 applications were tested as mitigation options for reducing N loss from the upland crop cultivation in the Haean catchment. Adopted mitigation option showed the significant potential for minimizing nitrate leaching rate and N_2O emission with maintaining the current crop yield mainly by reducing fertilization rates by about 35%. Splitting fertilizer application into 3 times (Split3) rather than 2 times (Split2) revealed even better results of decreasing nitrate leaching rate, N_2O emission through 2009 and 2010. Application of Split3 could reduce about 47 t N fertilizer and associated nitrate leaching rate and N_2O emission by 62% as compared to the application of conventional farming practices. This finding demonstrated the necessity to improve the farming practices of the Haean catchment. Reduced nitrate leaching would significantly decrease mean nitrate concentrations in the Mandae stream at the catchment outflow from 3.5 to about 2 mg l^{-1}, which is much closer to the quality standard of inland water of 1.5 mg l^{-1}. To the best of our knowledge this was the first study of upscaling N_2O emission and nitrate leaching including testing of mitigation options in order to reduce N losses from a catchment in South Korea by use of a process-based biogeochemical model. However, further studies are required to evaluate more detailed mitigation options such as cover crops (e.g. rapeseed and winter wheat which have been already started by a cultivation experiment in Gangwon Province) and reduced tillage both potentially contributing also to increase of soil carbon stocks and soil fertility. Furthermore, adaptation of fertilizer management with fertilization only into the plant holes of rows and adjustment of timing of fertilization depending on actual weather predictions, which can be particularly important under monsoon climate conditions.

1.5 List of manuscripts and specification of individual contributions

Manuscript 1

Sina Berger, Youngsun Kim, Janine Kettering, Gerhard Gebauer (2013) Plastic mulching in agriculture - friend or foe of N_2O emissions?. Agriculture, Ecosystems & Environment 167C: 43-51. DOI: 10.1016/j.agee.2013.01.010

S. Berger	Idea, data collection and analysis, discussion, manuscript writing and editing
Y. Kim	Data collection and analysis
J. Kettering	Data collection and analysis
G. Gebauer	Idea, discussion, manuscript editing

Manuscript 2

Youngsun Kim, Sina Berger, Janine Kettering, John Tenhunen, Edwin Haas, Ralf Kiese (2014) Simulation of N_2O emissions and nitrate leaching from plastic mulch radish cultivation with LandscapeDNDC. Ecological Research 29: 441-454. DOI: 10.1007/s11284-014-1136-3

Y. Kim	Idea, data collection and analysis, discussion, manuscript writing and editing
S. Berger	Data collection and analysis
J. Kettering	Data collection and analysis
J. Tenhunen	Discussion, manuscript editing
E. Haas	Discussion
R. Kiese	Idea, discussion, manuscript editing

Manuscript 3

Youngsun Kim, Youngho Seo, David Klaus, Steffen Klatt, Edwin Hass, John Tenhunen, Ralf Kiese (under review) Estimation and mitigation of N_2O emission and nitrate leaching from intensive crop cultivation in the Haean catchment, South Korea

Y. Kim	Idea, data collection and analysis, discussion, manuscript writing and editing
Y. Seo	Data collection
D. Klaus	Data collection

S. Klatt	Data collection
E. Haas	Discussion, manuscript editing
J. Tenhunen	Discussion
R. Kiese	Idea, discussion, manuscript editing

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Chapter 2

Plastic mulching in agriculture-friend or foe of N_2O emissions?

Sina Berger[1], Youngsun Kim[2,3], Janine Kettering[4], Gerhard Gebauer[1]

[1] BayCEER-Laboratory of Isotope Biogeochemistry, University of Bayreuth, 95447 Bayreuth, Germany

[2] Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research (IMK-IFU), 82467 Garmisch-Partenkirchen, Germany

[3] Department of Plant Ecology, University of Bayreuth, 95447 Bayreuth, Germany

[4] Department of Agroecosystem Research, University of Bayreuth, 95447 Bayreuth, Germany

Abstract

Polyethylene (PE) mulching is a very common method in agriculture worldwide because the use of PE films can improve product quality and yield by mitigating extreme weather changes, optimizing growth conditions and extending the growing season. Other than the problem with disposal of the plastics hardly any other of its effects on the environment are known. To determine whether covering fields with PE films affects N_2O emission, we conducted two experiments: first, comparing N_2O emissions of furrows and PE-mulched ridges of a radish field which had received different amounts of N fertilizer and second, assessing whether PE mulching increases N_2O emissions from PE-mulched ridges in comparison to non-PE-mulched ridges and furrows of a non-fertilized field. To achieve those aims we took comparative closed chamber measurements in conjunction with a photoacoustic infrared trace gas analyzer during the growing seasons of 2010 and 2011 at a radish and soybean field site in South Korea. For the radish field site we found significant differences between the N_2O emitted by furrows and PE-mulched ridges and found extraordinarily low N_2O fluxes from those spots of the ridges which were totally PE-mulch-covered between plant hole openings. At the soybean field we observed that plant holes of PE-mulched ridges showed only 68% of the emission measured of soils around soybean plants of non-PE-mulched ridges, implying that PE mulching may decrease N_2O emissions. Since our result is contrary to very recent findings we consider the extremely low soil moisture at our sites as explanation for the differences. Because knowledge on how PE mulches affect production and emissions of greenhouse gases is very limited, our study contributes greatly to understanding N_2O emission behavior of PE-mulched, poor sandy soils in a temperate monsoon climate.

Keywords: N_2O flux, polyethylene (PE) film, soil moisture, soil temperature, NH_4^+ fertilizer

2.1 Introduction

Nitrous oxide (N_2O) is a greenhouse gas of special concern due to its high global warming potential per molecule (Rodhe 1990), its high contribution to the observed global warming at present (WMO 2006) and its involvement in the destruction of the ozone layer in the stratosphere (Cicerone 1987), although its atmospheric concentration of 323 ppb (global mean concentration in 2005 (IPCC 2007)) is rather low. Major sources of N_2O are agriculturally managed soils (Vitousek et al. 1997), which produce and release N_2O through microbial denitrification, nitrification and nitrifier denitrification (Wrage et al. 2001; Kool et al. 2011). An overall aim should be to reduce N_2O emissions from such soils.

Plastic mulching - covering soil with polyethylene (PE) plastic films - is being established worldwide as a method in agriculture to increase crop production not only by keeping soil temperature and water content high but also by restricting arable weed growth. One obvious drawback of the method is the problem with the disposal of the plastic film (Kyrikou and Briassoulis 2007), but other side effects of the method such as its influence on greenhouse gas emissions are still hardly investigated. N_2O emissions from arable soils are known to increase both with fertilizer application and after heavy rainfall events (Flessa et al. 1995), but emissions are also driven by soil temperature and moisture parameters (Shepered et al. 1991). Many studies have been published on how plastic films increase soil temperature and improve soil water dynamics (e.g., Ban et al. 2009; Díaz- Pérez 2010; Katan and Devay 1991; Zhang et al. 2011), which in combination with high inorganic N and organic matter contents and low O_2 concentration in the soil (e.g., Akiyama and Tsuruta 2003a, 2003b; Hayakawa et al. 2009; Yanai et al. 2011), may increase the N_2O production of such covered soils. Recently, Arriaga et al. (2011) and Nishimura et al. (2012) reported on increased N_2O production from agricultural soils covered with plastic mulch films.

Here we present two consecutive experiments: the first attempts to provide an overview on the amounts of N_2O emitted from agricultural soils under plastic mulching and second, assesses the effect of plastic mulching on N_2O emissions from poor and rapidly drying sandy soils in a temperate monsoon climate. Therefore, in 2010 we took comparative measurements of N_2O emissions at the soil/atmosphere interface of PE-mulched ridges and uncovered furrows of a radish field's plots which had received different amounts of nitrogen fertilizer and because of unexpected results we conducted one further experiment in 2011, comparing the N_2O emissions of PE-mulched and non-mulched ridges of an unfertilized soybean field. Both experiments were conducted in East Asia (Korea), where plastic mulching is an extensively used method in agriculture. We hypothesized that the plastic mulching would cause higher N_2O emissions due to the mentioned conditions underneath the plastic film which are considered to be favorable for N_2O production.

2.2 Methods

2.2.1 Study site

The study sites were located in the Haean catchmentin Yanggu County, Gangwon Province, South Korea. The agricultural soils of the catchment are mainly characterized as terric cambisols or even as anthrosols (IUSS Working Group WRB 2007) because of an artificial long-term addition of sandy soil on the top of the fields.

The 2010 experiment was conducted at the Punchball Tongil Agricultural Experimental Farm (38°17'42.471''N, 128°8'28.088''E, 420 m a.s.l), the 2011 experiment was conducted at a conventionally treated soybean field (38°16'26.211''N, 128°8'45.354''E, 452 m a.s.l). The study area falls within the East Asian monsoon climate and has an 11-year (1999-2009) average annual air temperature of 8.5°C and an annual precipitation of approximately 1577 mm, with 70% of the precipitation occurring as heavy rainfall between June and August. In recent decades, a shortening of the monsoon season, as well as an increase in the amount of precipitation, and the number of heavy rainfall days, was observed (Chung et al. 2004). However, 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. Due to clearly colder temperatures in March, April and May than during the 11-year mean there was a delay in the start of cropping by approximately two to four weeks.

The 2011 mean air temperature (8.4°C) was in accordance with the 12-year (1999-2010) average whereas precipitation amounts (1440 mm) were slightly lower. Most precipitation occurred in June (372 mm), July (596 mm) and August (148 mm).

2.2.2 Experimental design in 2010

On May 15, the previously fallow field was tilled. On May 31, a commonly used basal fertilizer (30% mineral NPK fertilizer with 4.2-2-1, 70% organic fertilizer, with C/N ratio 4.1:1 and an N content 186.7 kg / ha, SamboUbi, South Korea) was applied as granules and mixed in the top 15 cm of the soil to enhance soil fertility. On June 1, additional NH_4^+-urea fertilizer in a ratio of 7:3 was applied as a one-time top dressing (mineral NPK fertilizer 11-8-9 +3MgO+0.3B, KG Chemicals, South Korea) at 4 fertilizer N rates on June 1: N50, N200, N250, and N350, reflecting the application of 50, 200, 250, and 350 kg N ha^-

^{1}. The recommendations for highland radishes provided by the Rural Development Administration of Korea (RDA 2006) was 250 kg/ha. The plots (7x7 m) were arranged in a randomized block design with three replicates for the applied fertilizer amounts N50, N250 and N350 and there was one more additional plot which received the N200 treatment (Figure 2.1). On June 9, the top 20 cm of the soil was ploughed, implementing a ridge system (35 cm width and about 15 cm height) with a distance of 70 cm between the rows. The ridges were covered with impervious black PE mulch (see Figure 2.2) that contained one row of holes with a diameter of 6 cm every 25 cm along the ridge. Finally, on June 14, radishes were sowed on the top ridges at a rate of two - three seeds for each hole (Hungnong Seeds, South Korea). Weeding during the experiment was performed manually without the application of herbicides. This is not the common practice in this area as farmers usually seem to apply herbicides, but in order not to add any more chemicals and potentially N_2O-emission-causing substances, it was decided to do manually weed. The weeding was done weekly during the month after the seeding of the radish. On August 27, the radish was harvested, the PE mulch was removed and the field lay fallow.

Each N50-, N250- and N350-radish field plot contained three polyvinylchloride (PVC) cylinders (see Figure 2.1). There were two of those cylinders on the PE-mulched ridge: the first one surrounded a hole with one radish plant (plant hole cylinder) and the second one was installed on the PE mulch (PE mulch cylinder). The PE mulch cylinder was accomplished by cutting a hole of the size of the PVC cylinder in the PE mulch, installing the PVC cylinder and then placing the PE mulch in the PVC cylinder. The PE mulch which surrounded that PVC cylinder was placed on the PVC cylinder from its outside so that the PE mulch of the ridge remained impervious. The third cylinder of each plot was installed in the furrow (furrow cylinder). The N200 plot had nine PVC cylinders, three in the furrow, three in the PE mulch and three more surrounding plant holes. Prior to seeding and after the harvesting N_2O flux measurements were taken on the fallow soil.

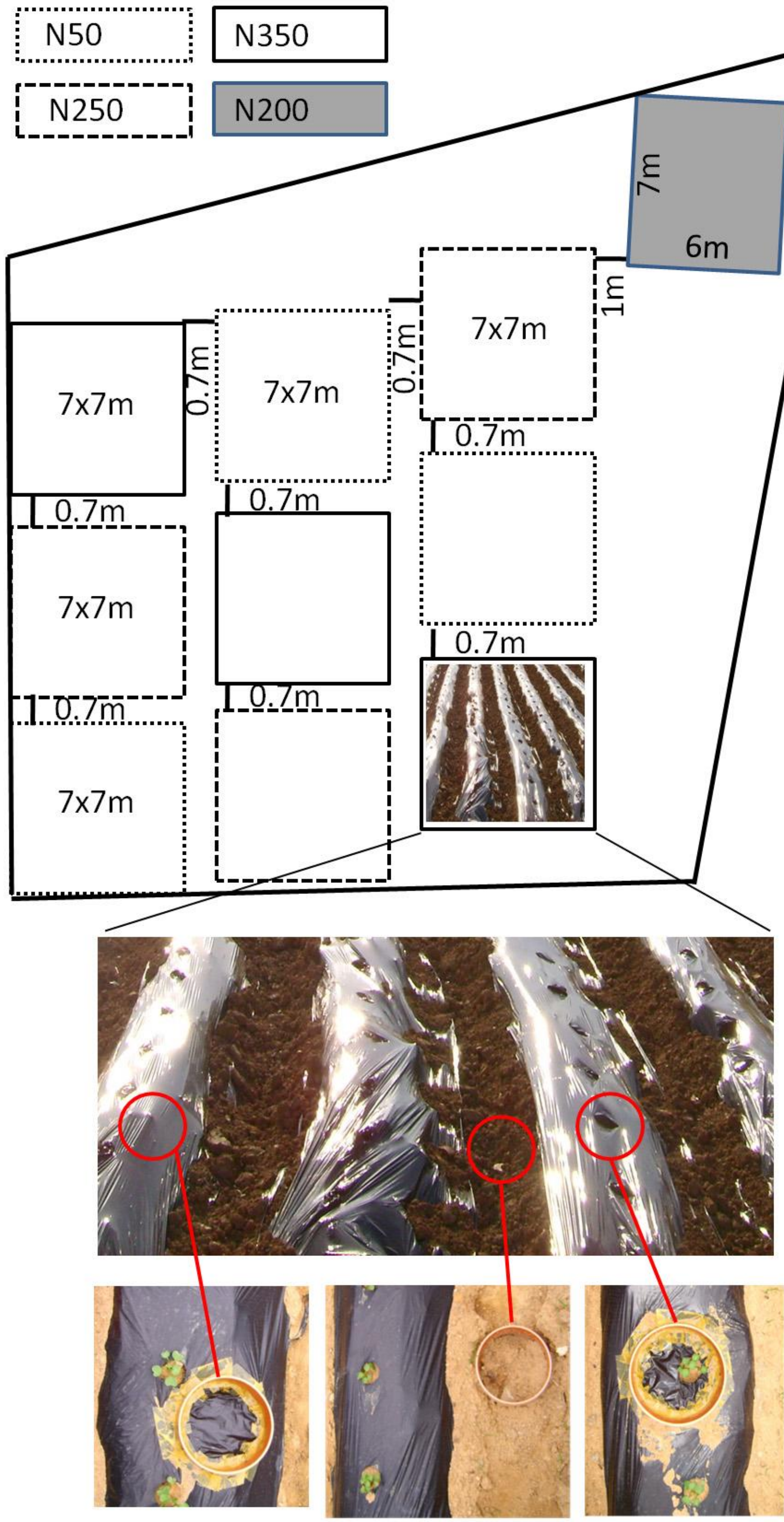

Figure 2.1 Schematic drawing of the experimental design of the radish field site in 2010

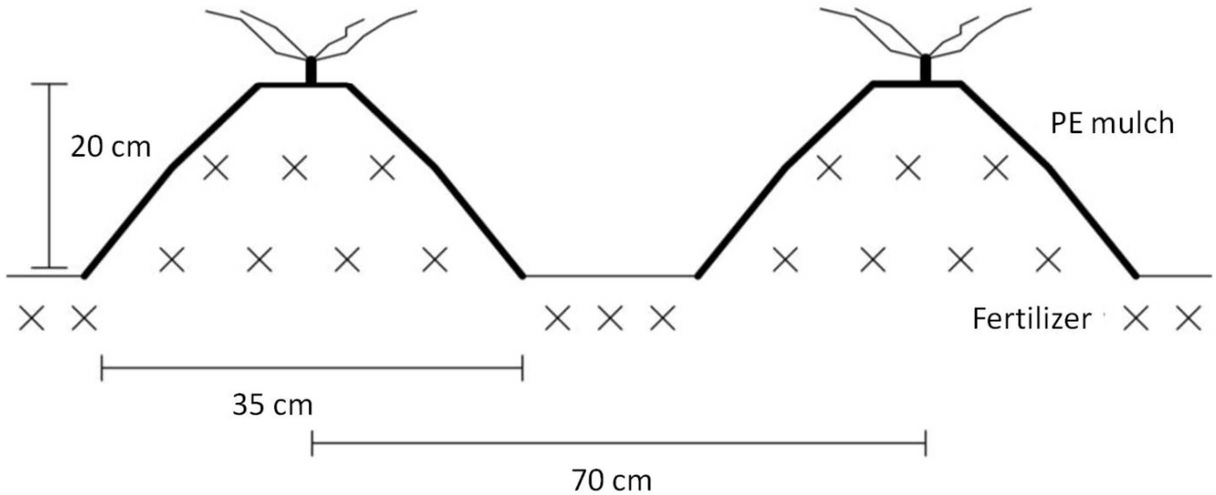

Figure 2.2 Scheme of a typical ridge cultivation system with plastic mulching in a temperate South Korean area with summer monsoon. Shown are the distributions of N fertilizer in the system and width, height and distance of the ridges

2.2.3 Experimental design in 2011

Before the experiment started, the field in which radish had grown the previous year, was ploughed by the farmer without applying any fertilizer in 2011. The ridge and furrow system was implemented (35 cm wide and 15-20 cm high (Figure 2.2)), the ridges were covered with impervious black PE mulch that contained one row of holes every 25 cm along the ridge with a diameter of 6 cm. On May 29, soybeans were sowed on top of the ridges at a rate of two - three seeds for each hole. Some ridges remained uncovered. Weeding during the experiment was performed manually without the application of herbicides. This is not the common practice in this area as farmers usually seem to apply herbicides, but in order not to add any more chemicals and potentially N_2O-emission-causing substances, it was decided to manually weed. The weeding was done one time, on June 15, 2011.

N_2O fluxes were measured using nine PVC cylinders: three surrounded soybean plants which grew on ridges covered with PE mulch, three surrounded soybean plants which grew on ridges which were not covered with PE mulch and three installed in the furrows which were randomly distributed next to PE-covered and non-PE-covered ridges.

2.2.4 Measurements of N_2O fluxes

N_2O fluxes were measured every three to seven days from May 13 through October 22, 2010 at the radish field site and from May 16 through September 14, 2011 at the soybean field site using the closed chamber method in conjunction with a photoacoustic infrared gas analyser (Multigas Monitor 1312, INNOVA, Ballerup, Denmark) as described by Yamulki and Jarvis (1999) and Goldberg et al. (2008). Each site contained the amount of PVC cylinders described above with a diameter of 19.5 cm and a height of 15 cm, which were installed 7 cm deep in the soil. They served as connecting points to attach the chambers in whose headspaces the N_2O concentrations were determined in 0, 10, 20, 30 and 40 minute intervals. The reproducibility of one single N_2O concentration measurement was ± 32 ppb. From a linear increase or decrease of the N_2O concentration in the chambers' headspaces the N_2O flux was calculated taking into account the total chamber volume which includes the chamber headspace volume, volume of the two 25 m long Teflon tubes and of the CO_2 and H_2O gas traps.

Cumulative N_2O emissions were calculated as described by Tilsner et al. (2003a), by multiplying the N_2O emission rates of two consecutive measurement days with the corresponding time period. These time weighted N_2O flux means were then summed up over the measurement period.

2.2.5 Measurement of soil moisture and soil temperature

To measure volumetric soil water content [%] and soil temperature [°C] ECH2O loggers (EM50 Data logger, Decagon Devices, WA, USA) were used. They logged soil moisture and temperature values every 30 minutes from May 13 through August 31, 2010 at the N200 treatment of the radish field and from May 16 through September 14, 2011 at the soybean field. At the N200 treatment of the radish field one sensor was installed 5 cm deep in the furrow and a second sensor was installed 5 cm deep in one of the holes of the PE mulch.

At the soybean field one sensor was installed 5 cm deep in a furrow, one more sensor was installed 5 cm deep in one of the plant holes of a ridge that was covered with PE mulch and a third sensor was installed next to a plant of a ridge which was not covered with PE mulch.

2.2.6 Statistical methods

N_2O flux curves were obtained by calculating mean N_2O flux values ± 1SE for every day of measurement and linear interpolation between two consecutive measurement days. The mean flux was based on n=3 for furrows, PE mulches and plant holes at each amount of fertilizer applied. Statistics were conducted with R 2.12.0. *Via t*-Test (normally distributed data) or Mann-Whitney *U*-test (not normally distributed data) it was tested whether the measured N_2O fluxes are significantly different from zero and whether the soil moisture and temperature conditions underneath the PE mulch were different from those in the furrow. After the t-Test had not shown a difference between the soil temperatures of PE-mulched ridges and furrows, a paired t-Test was conducted. To determine whether furrow-, PE mulch- and plant hole N_2O fluxes of the radish field's N50, N200, N250 and N350 plots and also the N_2O fluxes of the soybean field's PE-mulched and non-PE-mulched ridges, as well as soil moisture or soil temperature of the soybean field's furrows, PE- and non-PE-mulched ridges were statistically different from each other, t-Tests, ANOVAs or the non-parametric Kruskal-Wallis-tests were calculated. Pearson or Spearman analyses were performed to identify potential correlations between N_2O fluxes and volumetric soil water content and soil temperature and between the cumulative N_2O emissions and the amount of N fertilizer applied.

2.3 Results

2.3.1 N_2O fluxes and cumulative N_2O emissions at the radish field in 2010

With increasing amount of fertilizer applied there appeared to be a higher N_2O emission rate of the plant hole-spots at all the plots` ridges. The N_2O-emissions of the furrow showed a more complicated pattern: for those plots which had received a lower amount of N fertilizer (N50 and N200), the N_2O emissions of the furrows exceeded the emissions of the plant holes. For the N250 and N350 plots the opposite N_2O emission pattern could be observed.

The N_2O fluxes of ridges with PE mulch were almost zero for all of the treatments during the time of the experiment, except for June 23, when they reached their maximum (N50: 3.15 µmol m^{-2} h^{-1}; N200: 1.85 µmol m^{-2} h^{-1}; N250: 1.21 µmol m^{-2} h^{-1}; N350: 2.84 µmol m^{-2} h^{-1}). On that day, the plant holes and furrows also showed the highest N_2O fluxes. Before June 16 and after July 24 only very tiny to zero N_2O fluxes could be measured. There were significantly different N_2O fluxes ($^*p < 0.05$) between PE mulch and plant holes in PE mulch as well as furrows for almost all of the plots (see Table 2.1 in the appendix for all statistical differences). No differences were found among ridges, furrows and PE mulches of the differently fertilized plots.

The measurement period's cumulative N_2O emissions of the furrows and plant holes in PE mulch range between 2 to 6 mmol m^{-2} (equals 880.3 to 2640.8 g N_2O ha^{-1} or 5.5 to 16.4 g N_2O ha^{-1} d^{-1}), whereas the highest cumulative N_2O emissions degassed from the furrows of the N50 plots (6 mmol m^{-2}, equals 2640.8 g N_2O ha^{-1} or 16.4 g N_2O ha^{-1} d^{-1}). Among all of the different amounts of fertilizer applied the N_2O fluxes of the PE mulches integrated over time amounted to comparably low values of 0.2 to -0.8 mmol m^{-2} (equals 88.0 to -352.1 g N_2O ha^{-1} or 0.5 to -2.2 g N_2O ha^{-1} d^{-1}).

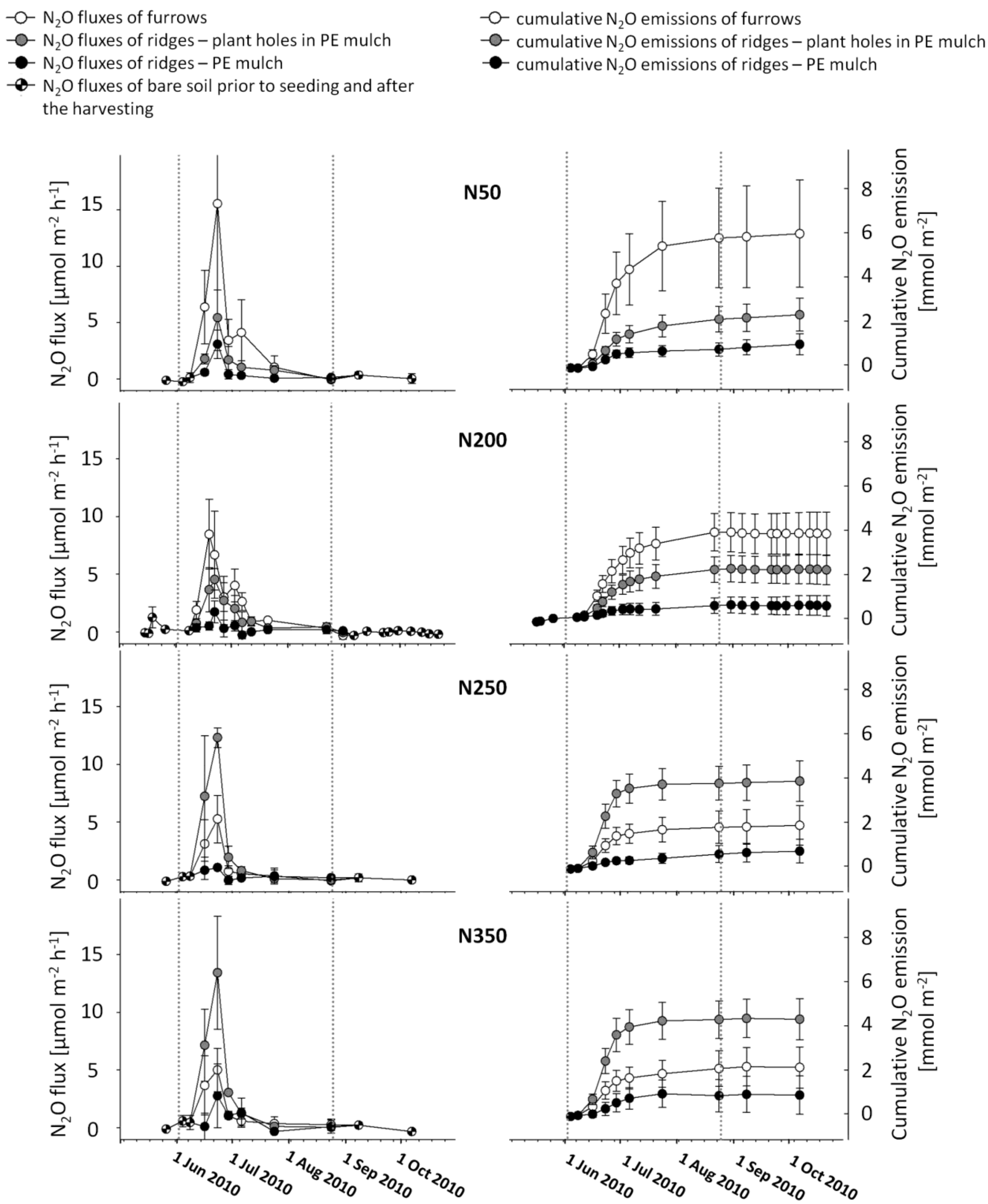

Figure 2.3 N_2O flux [µmol m^{-2} h^{-1}] and cumulative N_2O emission [mmol m^{-2}] of the radish field site from May 13 through October 22, 2010. The first dotted line indicates the day when the N fertilizer was applied (June 1) and the second dotted line indicates the day when the radish was harvested, the PE mulch

was removed and the ridge and furrow system was dissolved. Error bars in N_2O flux- and cumulative N_2O emission- graphs represent the standard error of the mean (n = 3)

2.3.2 Soil moisture and temperature of the PE-mulched ridges and furrows at the N200 plot

There appeared to be higher temperature fluctuations in the PE-mulched ridges than in the furrows; however, the mean soil temperature during the time of the experiment was 24.80°C (±2.14) in PE-mulched ridges and 24.30°C (±1.58) and furrows (Figure 2.4) which makes a very significant difference of 0.5°C (**p = 0.005). In contrast, the mean volumetric soil water content in ridges and furrows differed with a mean value of 19.80% (ranging from 10% to 32%) in the furrows and 15.62% (ranging from 5% to 15%) in the ridges underneath the PE mulch, which makes a highly significant difference (***$p < 0.001$) of 4.18%.

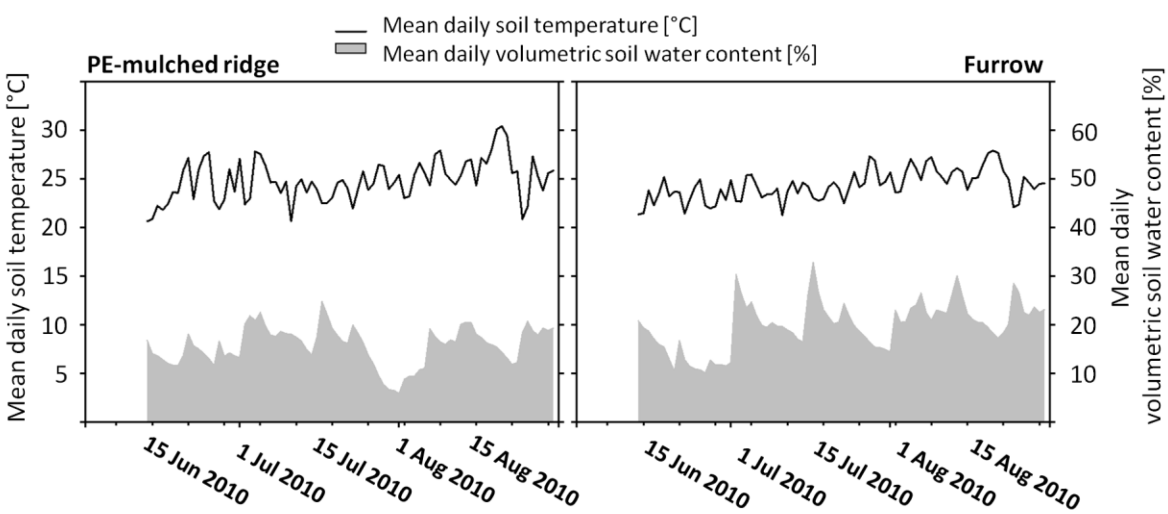

Figure 2.4 Mean daily volumetric water content [%] and mean daily soil temperature [°C] from June 14 through August 31 of the N200 plot at the radish field site in 2010

2.3.3 N_2O fluxes and cumulative N_2O emissions at the soybean field in 2011

The N_2O fluxes at the soybean field site's PE-covered and non-PE-covered ridges ranged from slightly negative to 5.2 µmol m^{-2} h^{-1} (Figure 2.5). During the time of the experiment they were comparatively low: flux peaks occurred on May 22, June 6, July 6, August 23 and August 30; however, statistically significant differences between the PE-mulched and non-PE-mulched ridges could not be found. For the furrows there is a similar pattern; however, their average N_2O exchange at the soil/atmosphere interface most of the times was higher than that of the ridges (Table 2.2).

For the cumulative N_2O emissions the graph (Figure 2.5) shows a difference between the amount of N_2O degassed from PE-covered and non-PE-covered ridges which is not statistically significant. Also, the amount of N_2O degassed from the furrows (Table 2.2) exceeds both the cumulative N_2O emissions of the PE-covered and non-PE-covered ridges. The N_2O fluxes of the non-PE-mulched ridges amounted to 3 mmol m^{-2} (equals 1320.4 g N_2O ha^{-1} or 10.9 g N_2O ha^{-1} d^{-1}), which is 50% more than the emission from the PE-mulched ridges. The highest cumulative N_2O emissions were found for the furrows (3.9 mmol m^{-2} equals 1716.5 g N_2O ha^{-1} or 14.2 g N_2O ha^{-1} d^{-1}).

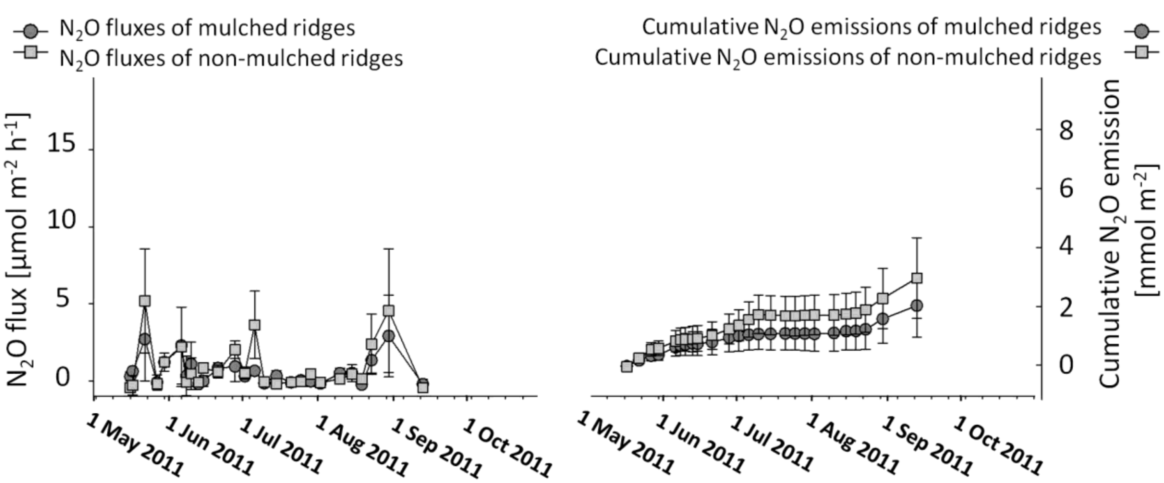

Figure 2.5 N_2O flux [µmol m^{-2} h^{-1}] and cumulative N_2O emission [mmol m^{-2}] of the soybean field site from May 15 through September 14, 2011. Error bars represent the standard error of the mean (n = 3)

Table 2.2 N_2O flux [µmol m^{-2} h^{-1}] and Standard Error (n = 3) as well as cumulative N_2O emission [mmol m^{-2}] and Standard Error (n = 3) of the soybean field site's furrows from May 15 through September 14, 2011. Those N_2O fluxes are a mixture of N_2O fluxes from furrows which were located next to PE-mulched and such which were located next to non-PE-mulched ridges so that they cannot be included into Figure 2.5

Date	Measured N_2O flux [µmol m^{-2} h^{-1}]	±1SE	Cumulative N_2O emission [mmol m^{-2}]	±1SE

16.05.2011	-0.29	0.18		
17.05.2011	0.40	0.56	0.00	0.00
22.05.2011	7.83	4.62	0.50	0.09
27.05.2011	0.23	0.41	0.98	0.19
30.05.2011	1.24	0.69	1.03	0.20
06.06.2011	3.03	2.12	1.34	0.32
08.06.2011	0.42	0.15	1.42	0.36
10.06.2011	0.95	0.09	1.46	0.39
13.06.2011	0.55	0.18	1.51	0.42
15.06.2011	1.02	0.08	1.55	0.43
21.06.2011	0.97	0.54	1.69	0.45
28.06.2011	1.95	1.58	1.93	0.50
02.07.2011	1.35	1.37	2.09	0.53
06.07.2011	3.30	2.53	2.31	0.54
10.07.2011	0.52	0.18	2.50	0.54
15.07.2011	0.50	0.43	2.56	0.56
21.07.2011	0.05	0.05	2.60	0.57
25.07.2011	-0.09	0.10	2.60	0.58
29.07.2011	0.14	0.30	2.60	0.59
02.08.2011	0.38	0.30	2.63	0.61
10.08.2011	0.53	0.49	2.71	0.63
15.08.2011	2.83	2.19	2.91	0.66
19.08.2011	-0.05	0.47	3.05	0.67
23.08.2011	2.16	1.09	3.15	0.69
30.08.2011	2.19	1.91	3.51	0.84
13.09.2011	0.15	0.36	3.91	1.09

2.3.4 Soil moisture and temperature of the PE mulched ridges, the non-PE-mulched ridges and furrows at the soybean field

The lowest mean soil temperature (21.47°C±2.44) as well as the smallest temperature fluctuations occurred in the furrows (Figure 2.6), whose soil temperatures were only by trend (p = 0.103) different from mean daily soil temperatures in the PE mulched and non-PE-mulched ridges. The temperature fluctuations and averaged mean daily soil temperature were very similar in PE-mulched (21.96°C±2.57) and non-PE-mulched ridges (22.00°C±2.56). Volumetric soil water content was very similar and statistically not differentiable in the furrows (30.22±0.11%) and non-PE-mulched ridges (28.36±0.08%), whereas the ridges which were covered with the PE film were much drier and statistically different (19.03±4.98%), which is reflected in a highly significant statistical result of $p < 0.001$, H = 86.684.

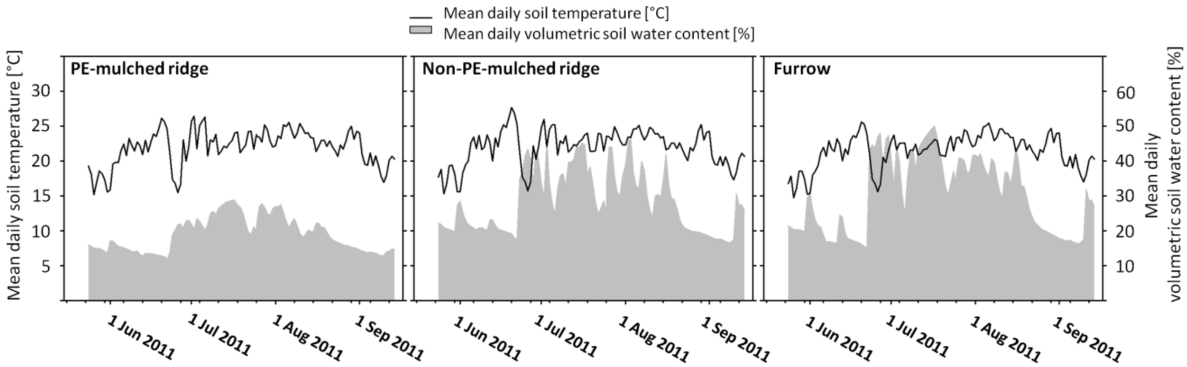

Figure 2.6 Mean daily volumetric water content [%] and mean daily soil temperature [°C] from May 15 through September 14 at the soybean field site in 2011

2.3.5 Correlations between N_2O fluxes and soil moisture, soil temperature and amount of N fertilizer applied

Neither soil moisture nor soil temperature affected the N_2O fluxes at the radish or soybean field site significantly ($r^2 < 0.1$, $p > 0.05$) even though the rain event from June 12 through June 14 apparently triggered the N_2O fluxes and the July 2 through July 5 rain event preceded one more, smaller, N_2O peak at the radish field site in 2010. No correlation could be found between applied N fertilizer amounts and sum of N_2O emitted from the radish field.

2.4 Discussion

2.4.1 General comments on crop yields of the study region

The average yield of radish in the study area in 2010 was 33.1 t ha^{-1} and in 2011, 32.5 t ha^{-1}; average yield of soybeans was 1.85 t ha^{-1} in 2010 and 1.56 t ha^{-1} in 2011 (Yanggu County office statistic 2010, 2011, unpublished data sheets). For radish the average yield data given in the literature varies between 60 and 160 t ha^{-1} and for soybeans the average yields are 0.6-4.9 t ha^{-1} (Batti et al. 1983; Morgan and Midmore 2003; Khairul Alam et al. 2010; Steve Lindner, personal communication 2012). Therefore, the yields of soybeans of the study region were on average whereas radish yields were below average. For other crops of the study area which also experience the PE mulching practice such as potato and cabbage, the yields are well on average in comparison to other areas' yields (Horton et al. 1988; Hassal and Associates 2003; Rahemi et al. 2005; Bohl and Johnson 2010).

Also, it is known that the PE mulch - through performing as a greenhouse - in general has a positive effect on the plant productivity, which is the main reason why it is widely used worldwide. The purpose of our study was not to reconfirm it but we took the already well-investigated positive PE mulching effect on crop yields (Kyrikou and Briassoulis 2007) as given and furthermore tried to broaden our knowledge on side effects of the PE mulch, such as its impact on N_2O as its impact on N_2O emissions.

2.4.2 Discussion of the results

An unexpected result was that the soil moisture of the PE-mulched ridges of the radish field as well as those of the soybean field was much lower than we had expected and as other publications predict (Kyrikou and Briassoulis 2007; Nishimura et al. 2012). Nishimura et al. (2012) observed that during the summer the soil moisture under the PE mulch at their experimental site ranged from 26% to 33%, which is in contrast to the considerably lower soil moisture values underneath the PE mulch that we found at our study sites: during the early summer drought period in 2010 it ranged from 9% to 22% at the radish field site and during the early summer drought of the year 2011 it ranged from 12% to 20%. The reason for those low soil moistures could be the soil conditions of the study area. According to Kettering et al. (2013), the soils of the study region were very sandy, as were the soils of our experimental sites. Such soils show a fast infiltration and seepage of water; thus due to quick seeping of water it appears plausible to us that the PE mulch at our experimental sites could not keep the soil moisture high and the soils of our experimental sites were dryer as in the previous studies. This unexpected finding may be the main reason why our initial hypothesis could not be corroborated. We were assuming that plastic mulch films covering agricultural fields would lead to increased N_2O emissions due to higher soil temperatures and moisture but the two experiments which we conducted were not in line with this hypothesis.

The 2010 experiment at the radish field site provided an indication that ridges which are being covered with PE mulch films show very tiny N_2O emissions from the PE mulch surface whereas the adjacent plant hole spots and furrows showed quite high emissions. This raised the question whether less N_2O production occurred underneath the PE mulch film or there was horizontal diffusion of N_2O from the ridge soil covered with the mulch film to the adjacent furrows and plant holes, so that most of the N_2O produced underneath the PE mulch would have degassed from the furrows and plant hole spots. Recently, Nishimura et al. (2012) published that the N_2O flux by permeation through the mulch film was much higher than that by horizontal diffusion to the furrow, that N_2O permeates through PE mulch film and that its permeability increased with increasing ambient temperature in a way that extremely huge amounts of N_2O degassed through the PE mulch film from the field during midday temperatures in the summer. Ou et al. (2007) also found that another gas the fumigant methyl bromide injected to the soil covered with a PE film was emitted to the atmosphere by permeation through the film to a great extend. Considering that the PE mulch is permeable for gas at high temperatures and the high mean daily soil temperatures of up to 30°C at our site, we conclude that the amount of N_2O degassing from the PE mulch surface to a great extend must have been in accordance with the amount of N_2O that had been produced underneath.

To us it makes sense that low soil moistures as well as high soil temperatures (the conditions underneath the PE mulch at our study sites) lead to a decreased N_2O production even though there are recent previous studies (Arriaga et al. 2011; Nishimura et al. 2012), that suggest otherwise, although at higher soil moistures. Assuming that N_2O is mainly produced during microbial denitrification (Tilsner et al. 2003b) and the recently attention attracting process of nitrifier denitrification (Wrage et al. 2001; Kool et al. 2011), processes which are known to occur at conditions of low oxygen - however the first process mainly takes place at low soil moisture, whereas the latter process takes place when moisture conditions are sub-optimal for denitrification (Linn and Doran 1984; Kool et al. 2011) - there would be less production of N_2O underneath the PE cover.

Interestingly, we neither found significant correlations between N_2O fluxes and soil moisture or temperature nor between N_2O fluxes and amount of fertilizer applied, which would have been an expected result since soil water content, soil temperature and fertilization rates have been identified as main drivers of N_2O fluxes (Dobbie et al. 1999; Ruser et al. 2006; Kool et al. 2011; Nishimura et al. 2012). A previous study which had been conducted in nearby forest sites had shown that there were significant correlations between N_2O fluxes and soil moisture and temperature (Berger et al. 2013).

However, despite not finding a correlation between moisture and N_2O fluxes, it was obvious that the rain event from June 12 to June 14, 2010 had triggered the N_2O fluxes of the radish field. This is consistent with previous studies reporting on greatest N_2O fluxes after the first of summer rains (Davidson et al. 1993; Scholes et al. 1997; Barton et al. 2008). Because the 2010 experiment left so many questions unanswered, we conducted the soybean field experiment in the following year in order to directly compare whether covered or uncovered ridges of a non-fertilized field would show higher N_2O emissions. The interesting result was that the amount of N_2O cumulatively emitted from plant holes of ridges which were covered with the PE mulch (2 mmol m^{-2}) was only 68% of the emission of soils around soybean plants of non-PE-mulched ridges (3 mmol m^{-2}) and it was only 50% of the N_2O emitted from the furrows (3.9 mmol m^{-2}) even though hardly any statistical significant differences could be found between N_2O fluxes at both PE-mulch-covered and –non-covered ridges on the single measurement days. The difference between soil moisture of the PE-mulched ridges and the non-PE-mulched ridges and furrows was even more pronounced than the differences between furrows and PE-mulched ridges in 2010. Thus, our results suggest that PE mulch may reduce N_2O emissions from agricultural fields on sandy soils in temperate areas with summer monsoon like in Korea because the PE mulch keeps the covered soils between the plant holes, where no water can infiltrate into the ridges, at lower soil moisture and higher soil temperatures.

Only taking into account the radish field data, one may argue that there might have ocurred a strong N_2O diffusion to, and stack effect through, the adjacent plant holes and furrows. But since a direct comparison of N_2O emissions of plant holes of PE-mulched ridges and plant spots of non-mulched ridges in the following year showed that mulched ridges certainly do not have higher emissions (if not even lower ones), we believe that PE mulches and the way they are used in Korea (application of fertilizer and PE mulching long before the most of the rainfall occurs, so that most of the fertilizer can get assimilated by the crops) can reduce N_2O emissions from agricultural soils.

To finally answer the title question: “Plastic mulching in Agriculture – friend or foe of N_2O emissions?”, it would be necessary to take comparative N_2O flux measurements of furrows located next to PE-mulched ridges would behave in comparison to furrows located next to non-PE-mulched ridges, which has not been done so far. Considering that the PE mulching is a very common method in agriculture in East Asian countries such as Korea, Japan and China, and that its use is increasing in Africa, in the Middle East and also in Germany by 15 - 20% annually (Kwon et al. 2006; Kyrikou and Briassoulis 2007; FBAW information, 2007; unpublished data sheet), it is very important to acquire detailed knowledge on the PE mulch’s effects on the environment.

Our results support the general finding that N_2O fluxes from non-fertilized legume cropping systems, which have N fixation as an additional N source, are not necessarily greater than fluxes from N fertilized non-legume crops under similar climatic and management regimes (Helgason et al. 2005; Rochette and Janzen 2005; Parkin and Kaspar 2006; Stehfest and Bouwman 2006; Barton et al. 2008). The N_2O emitted from the non-fertilized soybean field site in 2011 amounted to 5.90 mmol m^{-2} (2.06 mmol m^{-2} for the PE-mulched ridges and 3.90 mmol m^{-2} for the furrow), which is very similar to the amount of N_2O that had degassed from the N200 plots at the radish field site in 2010, which had received an intermediate amount of nitrogen fertilizer.

2.5 Conclusions

Comparative N_2O flux measurements were conducted at a radish field in 2010 and at a soybean field in 2011 in order to elucidate if PE mulching of agricultural fields affected N_2O emissions. Whereas the PE-mulched rows of the radish field showed rather low N_2O emissions, the adjacent furrows and plant holes showed higher emissions among different amounts of nitrogen fertilizer applied, we considered the extremely low soil moisture at our study site to be responsible for the comparatively low N_2O emissions which could neither be correlated with soil temperature and moisture, nor amount of fertilizer applied. The experiment at the soybean field in 2011 brought the interesting result that PE-mulching might decrease N_2O emissions from agricultural soils if applied on sandy soils located in a temperate climate including an early summer drought and monsoon rains. One additional result was that the N_2O emitted by a non-fertilized PE-mulched legume field did not exceed the N_2O emitted by a non-legume field which had received an intermediate amount of nitrogen fertilizer, which supports earlier findings which state that cultivation of nitrogen fixing plants does not cause N_2O emissions above cultivation of non-nitrogen fixing plants and common nitrogen fertilizer use.

2.6 Acknowledgements

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2.8 Appendix

Table 2.1 Statistically significant differences between N_2O fluxes of PE mulches, plant holes and furrows of the N50, N200, N250 and N350 plots of those measurement days when such differences occurred. * indicates $p < 0.05$, ** indicates $p < 0.01$ and *** indicates $p < 0.001$

N50	16.06. 2010			23.06. 2010			29.06. 2010			06.07. 2010			24.07. 2010		
		PE mulch	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**
	Plant hole	* P = 0.036		**Plant hole**			**Plant hole**	P = 0.138		**Plant hole**	P = 0.173		**Plant hole**		
	Fur-row			**Fur-row**			**Fur-row**	* P = 0.044	P = 0.158	**Fur-row**	* P = 0.017	P = 0.093	**Fur-row**		

N200	12.06. 2010			19.06. 2010			22.06. 2010			03.07. 2010			07.07. 2010		
		PE mulch	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**
	Plant			**Plant**	P =		**Plant**	P =		**Plant**	P =		**Plant**	**P=	

	hole			**hole**	0.063		**hole**	0.121		**hole**	0.131		**hole**	0.003	
	Furrow	$P = 0.163$		**Furrow**	* $P = 0.029$	* $P = 0.029$	**Furrow**		* $P = 0.036$	**Furrow**			**Furrow**	$P = 0.151$	$P = 0.074$
	12.07.	2010		21.07.	2010										
		PE mulch	**Plant hole**		**PE mulch**	**Plant hole**									
	Plant hole	* $P = 0.022$		**Plant hole**											
	Furrow	* $P = 0.018$		**Furrow**	*** $P < 0.001$	** $P = 0.006$									
N250	16.06.	2010		23.06.	2010		29.06.	2010		06.07.	2010		24.07.	2010	
		PE mulch	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**
	Plant hole			**Plant hole**	$P = 0.057$		**Plant hole**	* $P = 0.036$		**Plant hole**	$P = 0.056$		**Plant hole**		
	Furrow			**Furrow**	* $P = 0.029$	* $P = 0.011$	**Furrow**	$P = 0.109$	$P = 0.167$	**Furrow**			**Furrow**		
N350	16.06.	2010		23.06.	2010		29.06.	2010		06.07.	2010		24.07.	2010	
		PE mulch	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**		**PE mulch**	**Plant hole**
	Plant hole	* $P = 0.021$		**Plant hole**	* $P = 0.026$		**Plant hole**	** $P < 0.005$		**Plant hole**			**Plant hole**	*** $P < 0.001$	
	Furrow			**Furrow**		$P = 0.064$	**Furrow**	* $P = 0.015$	*** $P < 0.001$	**Furrow**			**Furrow**		

Given are those p-values which indicate a statistically significant difference as well as *p*-values which indicate a trend ($p \leq 0.1$). There were more measurement days but the table only provides the statistical results of such measurement days on which statistical differences between plant holes, PE-mulch and furrows could be found

Chapter 3

Simulation of N_2O emissions and nitrate leaching from plastic mulch radish cultivation with LandscapeDNDC

Youngsun Kim[1, 2], Sina Berger[3], Janine Kettering[4], John Tenhunen[2], Edwin Haas[1], Ralf Kiese[1]

[1] Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research (IMK-IFU), 82467 Garmisch-Partenkirchen, Germany

[2] Department of Plant Ecology, University of Bayreuth, 95447 Bayreuth, Germany

[3] BayCEER-Laboratory of Isotope Biogeochemistry, University of Bayreuth, 95447 Bayreuth, Germany

[4] Department of Agroecosystem Research, University of Bayreuth, 95447 Bayreuth, Germany

Abstract

Radish is one of the major dry field crops in Asia commonly grown with plastic mulch and high rates of N fertilization, and potentially harming the environment due to N_2O emissions and nitrate leaching. Despite the widespread use of plastic mulch, biogeochemical models so far do not yet consider impacts of mulch on soil environmental conditions and biogeochemistry. In this study, we adapted and successfully tested the LandscapeDNDC model against field data by simulating crop growth, C and N turnover and associated N_2O emissions as well as nitrate leaching for radish cultivation with plastic mulch and in conjunction with different rates of N fertilization (465 - 765 kg N ha^{-1} yr^{-1}). Due to the sandy soil texture and monsoon climate, nitrate leaching with rates up to 350 kg N ha^{-1} yr^{-1} was the dominant reason for overall low nitrogen use efficiency (32 - 43%). Direct or indirect N_2O emissions (calculated from simulated nitrate leaching rates and IPCC EF_{ind} = 0.0075) ranged between 2 - 3 kg N ha^{-1} yr^{-1}, thus contributing an equal amount to total field emissions of about 5 kg N ha^{-1} yr^{-1}. Based on our results, emission factors for direct N_2O emissions ranged between 0.004 - 0.005. These values are only half of the IPCC default value (0.01), demonstrating the need of biogeochemical models for developing site and/ or region specific EFs. Simulation results also revealed that changes in agricultural management by appling the fertilizer only to the rows would be an efficient mitigation strategy, effectively decreasing field nitrate leaching and N_2O emissions by 50 - 60%.

Key words: Biogeochemical modeling, LandscapeDNDC, N_2O, Nitrate leaching, Plastic mulch

3.1 Introduction

Agriculture is the major anthropogenic source of nitrous oxide (N_2O) (McCraw and Motes 1991; Smith and Conen 2004). Of global anthropogenic greenhouse gas (GHG) emissions, agriculture accounts for about 60% of N_2O emissions (IPCC 2007). N_2O emissions are directly related to the amounts of nitrogen application (Smith and Conen 2004) and have increased by 11% since 1990, primarily due to the increase in fertilizer use and the sectoral growth of agriculture (IPCC 2007). In Korea, agricultural N_2O emission is estimated at about 12 Gg, which accounts for about 24% of the total national N_2O emissions. Agricultural soils are the major source of N_2O, contributing about 58.3% to the total agricultural N_2O emissions (KEEI 2009a). N_2O emissions and nitrate (NO_3^-) leaching from cultivated soils are influenced by environmental factors such as soil temperature and water content, radiation, pH, Eh, and substrate concentration gradient, as well as management practices such as tillage, manure and fertilizer application, incorporation of crop residues (Li 2007; Smith et al. 2002) and plastic mulching (Nishimura et al. 2012). Worldwide, plastic mulch has been used for crop production since the 1960s (Lamont 2005). Over the last 10 years this form of agricultural management dramatically increased with China being the largest consumer of 40% of the global production (Kasirajan and Ngouajio 2012), and a total of 7 million ha of crop cultivation with plastic mulch (Li et al. 2004).

For many years the use of black and transparent plastic mulch has been widely utilized for various crops in Korea as well. In the traditional plastic mulching system, the crop is sown under the plastic film which is held tightly across the soil surface by covering the edges. The crop emerges through perforations in the plastic mulch, which are usually made at the time of seeding. The plastic mulch is discarded after harvest and new mulch is laid in the following season (Fisher 1995). In arid and semi-arid regions, crop growth is often limited by water. The amount of available water in soils can be increased by mulching (Wang et al. 2009b), since it is effective in improving water use efficiency by up to 25% (Chakraborty et al. 2010). The plastic mulch can also provide other benefits such as weed control, reduction in soil compaction and erosion and increase in soil temperature (Fisher 1995; Liakatas et al. 1986; Romic et al. 2003; Wan and El-Swaify 1999). Therefore, the plastic mulch performs like a greenhouse by capturing and retaining daytime solar radiation and reducing heat loss at night, producing a mini-greenhouse effect (Kwabiah 2004). However, less rainfall can infiltrate and pass through the root zone under the plastic mulch because part of the rain that falls onto an impervious plastic film covering a planting bed can run into the furrows (Haraguchi et al. 2004). A study by Haraguchi et al. (2003) revealed that only about 50% of the total precipitation infiltrated into the soil through plant holes on rows covered with plastic mulch.

In addition to the use of plastic mulch, Korean agriculture is characterized by high rates of nitrogen fertilization (Cho 2003; Lee et al. 2010) with potentially strong environmental impacts due to elevated N_2O emissions as well as NO_3^- leaching into aquatic systems. The latter is of uppermost importance, since the receiving reservoirs, in our case Soyang Lake, are major drinking water sources for urban areas including the city of Seoul. Radish is a typical Korean short duration crop cultivated with plastic mulch, mainly in the cool seasons of spring and autumn (Sirtautas et al. 2011). Due to its fast growing character (Akoumianakis et al. 2011; Deng et al. 2011b; Park et al. 2006; RDA 2006), farmers apply particularly high rates of N fertilizer (> 600 kg N ha^{-1}). In the recent past, process-based models were increasingly used to predict the impact of various agricultural management practices on plant nitrogen use efficiency and nitrogen losses to the environment, such as greenhouse gas emissions and NO_3^- leaching, by analyzing the interactions between management practices, primary drivers such as climate and soil properties and biogeochemical reactions (e.g. (Chirinda et al. 2011; Giltrap et al. 2010; Li et al. 2006; Liu et al. 2003)). Although black plastic mulch is a common farming technique in Korea and other parts of Asia, biogeochemical models do not yet consider the impacts of this technique on environmental conditions and soil biogeochemistry. In this study, we adapted and applied the LandscapeDNDC model (Haas et al. 2013) for simulation of crop growth, C and N turnover and associated N_2O emissions as well as NO_3^- leaching for typical Korean radish (*Raphanus sativus* L.) cultivation under plastic mulch, considering different rates of N fertilization.

3.2 Materials and Methods

3.2.1 Site description

The model was tested with data from summer radish fields (38.3°N, 128.14°E, 420 m a.s.l) in Haean Catchment, located in the northeast of Yanggu County, Gangwon Province, South Korea. The annual average air temperature is about 8.5°C and the annual precipitation is approximately 1,500 mm (Figure 3.1). More than half of the annual precipitation occurs during the monsoon season. Daily meteorological data for the simulation year 2010 such as precipitation, average temperature, wind speed, relative humidity and radiation was provided from an automatic weather station on site.

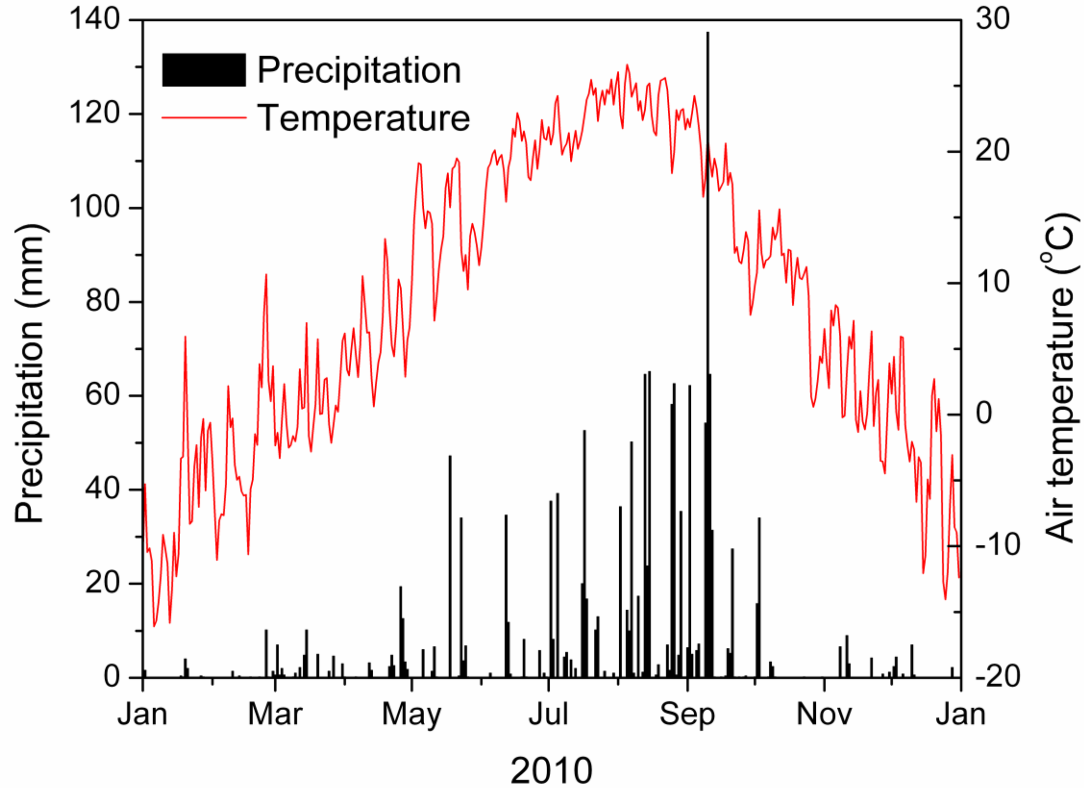

Figure 3.1 Daily precipitation and average daily air temperature of the study site. The weather data was collected from the automatic weather station on site in 2010

The soil of the site investigated was classified as Anthrosols (IUSS Working Group WRB 2007) characterized by very low soil organic carbon contents (SOC), slight acidification (pH 5.1 - 5.6) and high sand contents (> 10%) resulting in low values of field capacity and wilting point (Kettering et al. 2013). For more details see Table 3.1.

Table 3.1 Physico-chemical soil properties of the study site for 0 - 60 cm soil depth

Soil depth [cm]	BD[a] [g cm^{-3}]	pH	SOC[b] [%]	Sand [%]	Silt [%]	Clay [%]	SF[c] [%]	FC[d] [vol %]	WP[e] [vol %]
0 - 20	1.64	5.1	0.21	80.7	16.3	3.0	4.3	0.27	0.14
20 - 40	1.51	5.2	0.22	77.3	19.1	3.6	5.4	0.31	0.14
40 - 60	1.49	5.6	0.37	73.2	22.4	4.4	8.5	0.23	0.10

[a] Bulk Density, [b] Soil Organic Carbon, [c] Stone Fraction, [d] Field Capacity, [e] Wilting Point

3.2.2 Agricultural management

Mineral (187 kg N ha^{-1}) and organic N (228 kg N ha^{-1}) were applied as basal fertilisation to the entire field as a topdressing two weeks prior to the radish seeding. Mineral fertilizer contained about 4.2% N of the total as NH_4^+-N. Organic fertilizer consisted of bean cake (95%) and animal bones (5%) with N contents of about 7.7% and 5.3% N, respectively. To examine the impact of N fertilization on N_2O emissions, NO_3^- leaching and crop growth, the entire field was divided into subplots and in addition to basal fertilization, four different rates of mineral nitrogen (50, 150, 250 and 350 kg N ha^{-1}) were manually added on 4 replicated plots (49 m^2) per N treatment. All N treatment plots were plowed in 15 - 20 cm depth one week after fertilization in order to create rows and interrows. The rows were covered with black plastic mulch prior to radish seeding and the mulch had continuously covered the rows until harvest. About 2 or 3 radish (*Raphanus sativus* L.) seeds were sown per one plant hole on rows in mid-June. Detailed information for radish cultivation is shown in Table 3.2.

Table 3.2 Agricultural management for radish cultivation including different rates of N fertilizer application

Agricultural management	Date [dd/mm]	Rate [kg N ha^{-1}]
Seeding	14/06	
Basal fertilization		
Inorganic fertilizer ($(NH_4)_2SO_4$)	31/05	187
Organic fertilizer (Bean cake)	31/05	228
Additional fertilization		
Inorganic fertilizer ($(NH_4)_2SO_4$)	01/06	50, 150, 250, 350[a]
Tillage[b]	31/05, 09/06	
Harvest	31/08	

[a] 50, 150, 250 and 350 kg N were applied to each N treatment plot with 4 replicates
[b] Tilling depth is 15 - 20 cm

3.2.3 LandscapeDNDC: model description and adaptation

In this study the LandscapeDNDC (Haas et al. 2013) model was applied, which unifies functions of the agricultural-DNDC (Giltrap et al. 2010; Li et al. 2001) and the Forest-DNDC (Kesik et al. 2005; Kiese et al. 2011; Stange et al. 2000). LandscapeDNDC is a process-based biogeochemical model which simulates plant growth, ecosystem C and N cycling, the associated biosphere–atmosphere exchange of greenhouse gases (nitrous oxide: N_2O, carbon dioxide: CO_2 and methane: CH_4) and nitrogen leaching on the basis of plant physiological, microbial and physicochemical interactions. The model runs at sub-daily time steps and uses data such as maximum and minimum air temperature, precipitation, radiation, and wind speed as meteorological drivers. Further input data is needed to reflect agricultural management practices, e.g., planting/harvesting, tillage, fertilizer application, irrigation and information on soil and vegetation properties (SOC, bulk density, texture, pH and crop types) for site characterization and model initialization. Using these input data, LandscapeDNDC predicts soil environmental factors such as substrate availability (C and N), soil temperature and moisture as well as partitioning of anaerobic/ aerobic micro-sites for all user defined soil layers, which are finally driving microbial N turnover processes of nitrification and denitrification and associated losses of N_2O and NO_3^-.

Since LandscapeDNDC is a 1-dimensional model and, therefore, cannot consider small scale variation in soil topography, we conducted separate simulations of rows and interrows. To consider the effects of plastic mulch on soil moisture and temperature dynamics, we adjusted meteorological input data of rainfall and air temperature for row simulations based on measurements of soil environmental conditions (see section below). During the period when rows were covered with black plastic mulch (June 11th - August 31st), 90% daily maximum air temperature instead of average air temperature and only half of the daily precipitation data were used. The latter estimate is based on measurements at a nearby comparable field resulting in about 50% surface runoff formation from rainfall, mainly caused by plastic mulch cover (Arnhold et al. 2013). At times without plastic mulch and for total interrow simulations, actual measured weather data was used. LandscapeDNDC was initalized for a soil depth of 60 cm (Table 3.1) divided into 30 sub-layers of 2 cm dimension. All simulations used a model spin-up of 2 years carried out with the management applied in the 50 kg N treatment. Guided by information available from RDA (2002), we set main parameters for radish growth of MaxTDD (sum of daily temperature necessary for complete crop development), TLimit (minimum tempertaure for plant growth) and OptimumYield (potential yield under optimum conditions) to values of 1800°C, 5°C, 2465 kg C ha^{-1}, respectively.

3.2.4 Field measurements used for model validation

The LandscapeDNDC model was tested against field measurements of soil water and temperature, N_2O emissions, NO_3^- concentration in soil water and biomass development of radish crops. All field measurements used for model testing were conducted in the framework of the TERRECO project (Berger et al. 2013b) in 2010. Thereby, N_2O fluxes were measured by the closed chamber technique in conjunction with a photo-acoustic infrared trace gas analyzer from May (before seeding) to October (after harvest) in rows and interrows of each N treatment plot in 3 replicates (Berger et al. 2013b). ECH_2O

loggers (EM50 Data logger, Decagon Devices, WA, USA) were installed in each N fertilizer treatment row in order to measure soil temperature and water content at 15 and 30 cm depth every 30 minutes in 2 replicates. Suction lysimeters connected with a soil hydrological monitoring network of standard tensiometers were installed at soil depths of 15 cm in rows and at 30 cm in interrows in each of the 50, 150, 250 and 350 kg N treatment plots for quantification of soil water NO_3 concentrations in weekly sample intervals (Kettering et al. 2013). Data on radish biomass (dry weight from 8 radish plants per plot) were available for different developmental stages, i.e. at 25, 50 and 75 days after seeding.

3.2.5 Model performance criteria

The model performance was evaluated by the normalized root mean square prediction error (RMSPE) and coefficient of determination (r^2) based on following equations:

$$RMSPE = \sqrt{\frac{1}{N}\sum(X_{mea} - X_{sim})^2} \quad (1)$$

$$r^2 = \frac{\left(\sum(X_{mea} - \overline{X}_{mea})(X_{sim} - \overline{X}_{sim})\right)^2}{\left(\sum(X_{mea} - \overline{X}_{mea})^2 \sum(X_{sim} - \overline{X}_{sim})^2\right)} \quad (2)$$

Where X_{mea} is the measured value and X_{sim} is the simulated value. $\overline{X}_{mea}$ is the average value of field measurements and $\overline{X}_{sim}$ is the average value of model simulations. The coefficient of determination value of 1 indicates that there is strong correlation between measured and the simulated values (Chirinda et al. 2011). Significant difference of measured and simulated values was tested by the Wilcoxon signed-rank test (SPSS).

3.3 Results

3.3.1 Soil temperature and water content

LandscapeDNDC simulations of mean daily soil temperature and water content at 15 and 30 cm soil depth in rows of the 50, 150, 250 and 350 kg N fertilizer treatments were compared with field measurements. No measurements were available for interrow conditions. Figure 3.2 shows the correlation of simulated and measured soil temperature in 15 and 30 cm soil depth, including data of all N fertilizer treatments for average air temperature (default setting) and adjusted model input of 90% maximum air temperature. Using 90% of the maximum air temperature significantly reduced the absolute deviation of simulations from measured values and significantly increased the model´s prediction capacity (r^2 = 0.34 - 0.49). Since temperature measurements were based only on one sensor per N treatment and soil depth, higher values of r^2 might be hampered by uncertainties associated with the measured values, particularly taking into account a complex system of rows covered with black plastic mulch. Nevertheless, descriptive statistics of simulated and measured soil temperature in 15cm and 30cm soil depth revealed only small differences with respect to the mean (15 cm 23.7 vs. 23.9°C; 30 cm 22.5 vs. 23.1°C), minium and maximum values for the period of plastic mulch coverage.

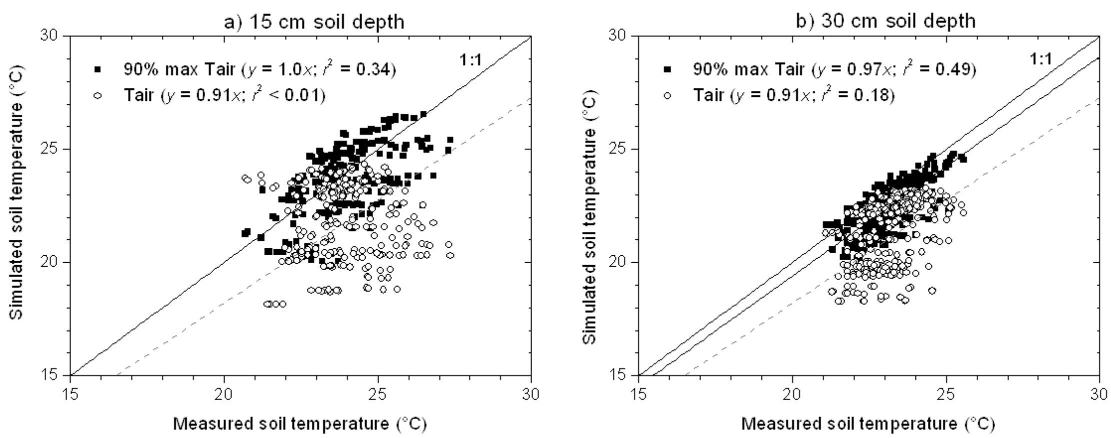

Figure 3.2 Comparison of measured and simulated temperature at a) 15 and b) 30 cm soil depth of rows including data of all N fertilizer treatments (Note: soil temperature across different treatments were not statistically different). Open circles represent simulated soil temperature with average air temperature (Tair) as input and closed squares represent simulated soil temperature with 90% of maximum air temperature of that recorded at the climate station on site as input. Lines (gray dashed: average air temperature; black solid: 90% maximum air temperature and 1:1 line) represent linear fit and prediction bands

In contrast to the soil temperature, measurements of soil water content at 15 and 30 cm soil depth differed across the N fertilizer treatments. The wide range of soil water content was observed at 30 cm depth, which ranged from 22.0 to 27.7 vol. %. The measured mean soil water content at 15 cm depth showed lower water content ranging from 17.9 to 19.3 vol. %. The comparison of time series of measured and simulated soil water content at 15 and 30 cm soil depth is presented in Figure 3.3, showing a high dynamic with several drying and re-wetting events over the growing season well captured by model simulations. Due to the high sand content, even after strong rainfall events, simulated and measured soil moisture barely exceeded 30 vol %. This indicated a high percolation rate and, consequently, rather low soil moisture conditions during the growing season.

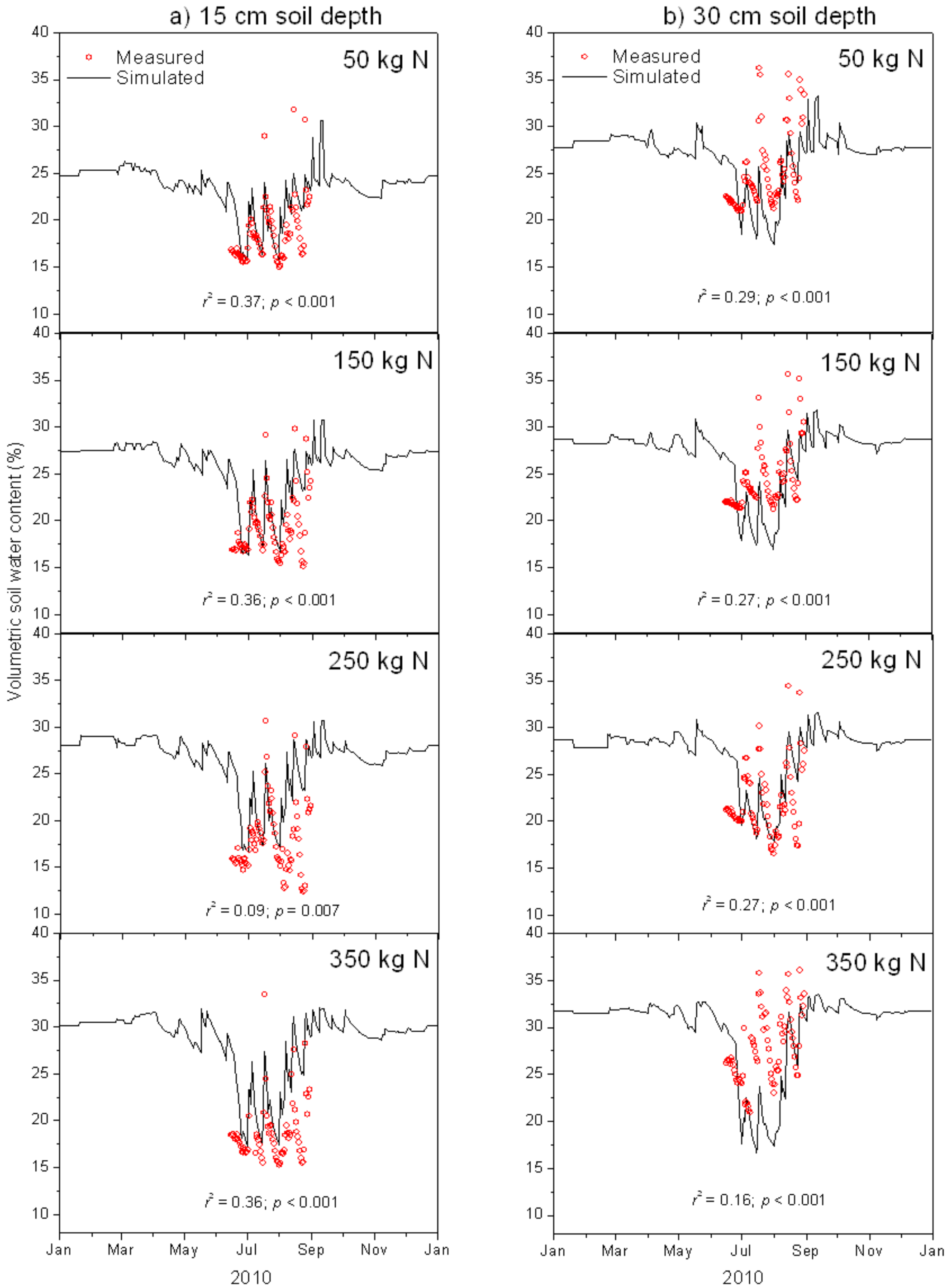

Figure 3.3 Measured (circle) and simulated soil water content (line) at a) 15 and b) 30 cm depth of rows with 50, 150, 250 and 350 kg N fertilizer treatments

3.3.2 Radish biomass

LandscapeDNDC model differentiates between simulation of above- and belowground biomass. The aboveground biomass includes leaves and stems, and the belowground biomass in the case of radish, fine roots and coarse roots. Comparison between measured and simulated biomass, as well as plant nitrogen content (data not shown) at the day of harvest, revealed that simulated belowground biomass was underestimated for 50, 250 and 350 kg N treatments, but slightly overestimated for 150 kg N treatment. The model overestimated aboveground biomass for all N treatments. Simulated and measured total biomass ranged between 4.0 - 5.4 t DW ha^{-1} and 4.4 - 5.6 t DW ha^{-1}, respectively (Table 3.3). Thereby, both measured and simulated radish biomass increased with higher rates of N fertilization. However, even though increasing fertilisation rates increased yields, nitrogen use efficiency was rather low and decreased from 43 to 32% when comparing the 50 and 350 kg N treatments.

Table 3.3 Measured and simulated radish biomass dry weight at the last harvest day (75 days after seeding). Note that N treatments have 187 kg N ha^{-1} mineral fertilizer and 228 kg N ha^{-1} of organic fertilizer addition prior to planting (details see Table 3.2)

N fertilizer treatments [kg N ha^{-1}]	Aboveground [t ha^{-1}][a]		Belowground [t ha^{-1}][b]		Total [t ha^{-1}][c]	
	Measured	Simulated	Measured	Simulated	Measured	Simulated
50	1.26	1.72	2.72	2.69	3.99	4.42
150	1.55	1.92	2.97	3	4.52	4.92
250	1.82	2.04	3.22	3.18	5.03	5.22
350	2.01	2.17	3.39	3.39	5.4	5.56

[a] Leaves and stems, [b] Roots , [c] Sum of above- and belowground biomass

Figure 3.4 shows the temporal development of measured and simulated radish biomass over the growing season. Model simulations agreed well with the measurements (r^2 = 0.82 - 0.88), even though radish biomass was overestimated in all N treatments at the first sampling date (25 days after seeding).

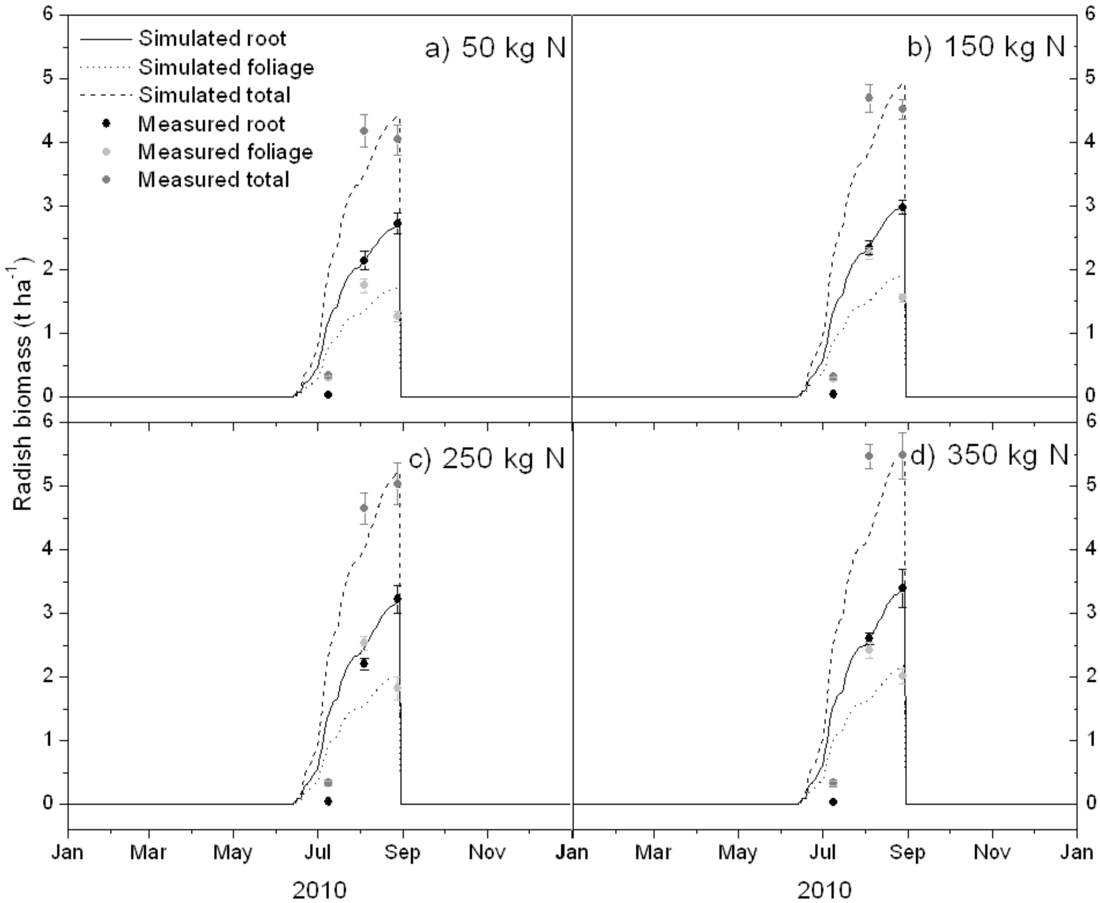

Figure 3.4 Comparison of measured (circle) and simulated (line) radish biomass dry weight from rows with 50, 150, 250 and 350 kg N fertilizer treatments. Above- and belowground radish biomass were measured at 25, 50 and 75 days after seeding. Bars represent standard errors of measurements

3.3.3 N_2O emissions

Simulated as well as measured N_2O emissions of all fertilizer treatments started to increase 3 days after fertilization in the rows and interrows and decrease to lower levels 2-3 months after fertilization (Figure 3.5). Both measured and simulated N_2O emissions from rows slightly increased (approx. 10%) with increasing rates of N fertilization. Peak emissions approximately 17 days after fertilization (> 100 µg N m^{-2} h^{-1}) were generally underestimated by model simulations for both row and interrow conditions. However, measurements during that period of time had very high uncertainties as indicated by the large error bars. Mean measured and simulated N_2O emissions in rows (considering only the period when measurements were available) ranged from 27.9 - 65.8 µg N m^{-2} h^{-1} and from 51.8 - 63.1 µg N m^{-2} h^{-1}, respectively (Table 3.4). N_2O emissions of interrows were not statistically different and measured and simulated fluxes ranged from 26.6 - 78.0 µg m^{-2} h^{-1} and 54.5 - 73.1 µg m^{-2} h^{-1}, respectively (Table 3.4). The LandscapeDNDC model overestimated mean N_2O emissions from interrows (3 out of 4 treatments) by about 100%, but was better for prediction of N_2O emissions from rows in 3 out of 4 treatments (< 40% overestimation). Taking into account the uncertainty of measurements and the low measuring frequency, the magnitude and temporal representation of N_2O emissions from rows and interrows overall was reasonably captured by model simulations with r^2 up to 0.45 and RMSPE ranging in the same order than mean measured values +/- standard deviation. For all data presented in Table 3.4 mean simulated values did not statistically differ from mean measured values.

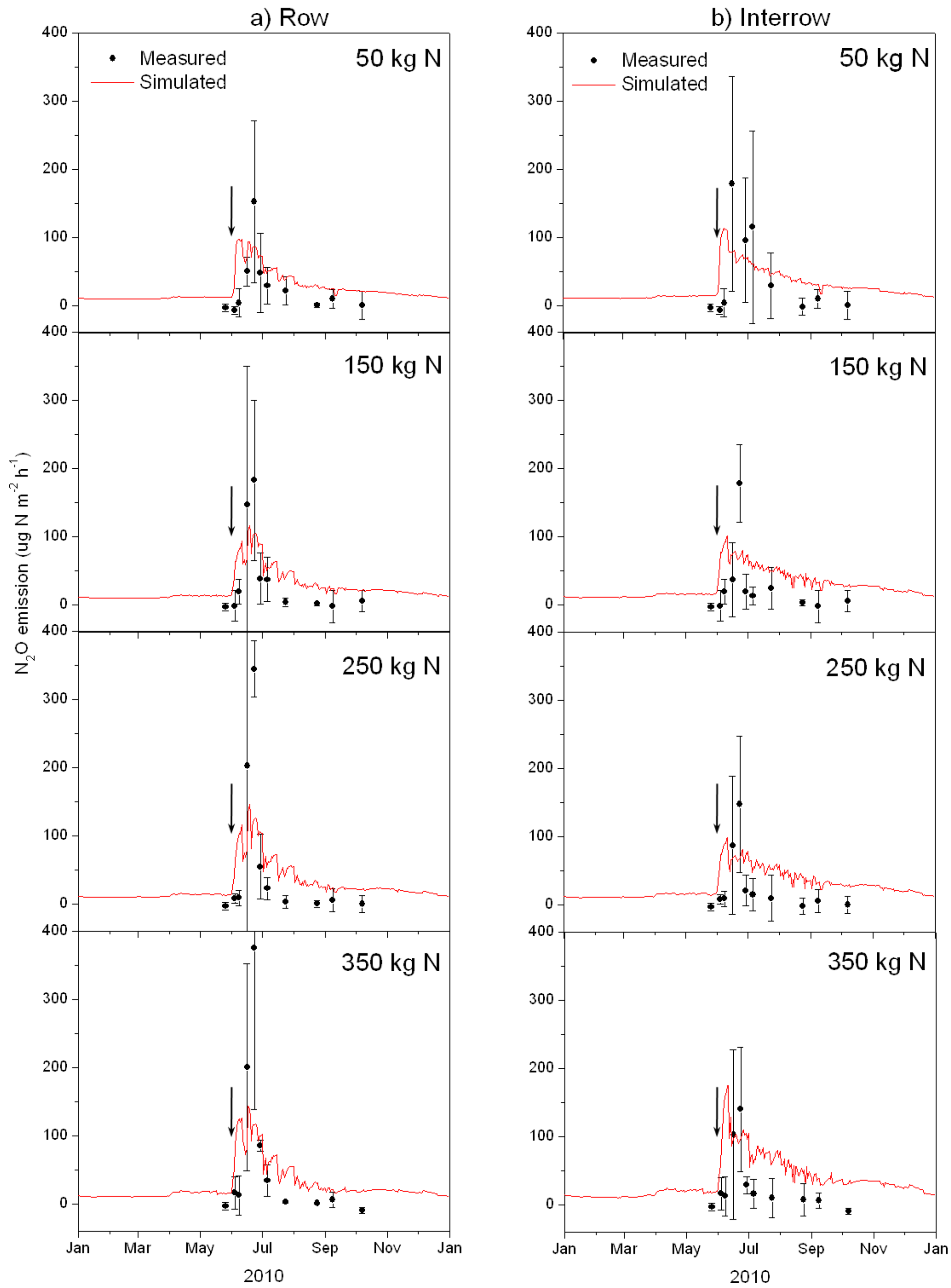

Figure 3.5 Measured (circle) and simulated (line) N_2O emissions from a) rows and b) interrows with 50, 150, 250 and 350 kg N fertilizer treatments. Arrows indicate time and date of N fertilizer application. Bars represent standard deviations of measurements

Table 3.5 shows annual N_2O emissions as calculated from daily simulations of LandscapeDNDC for row and interrow conditions of all fertilizer treatments. Direct N_2O emissions in rows and interrows increased with increasing rates of N fertilization from around 2 to 3 kg N_2O-N ha^{-1} yr^{-1}. Direct N_2O emission factors for rows and interrows were 0.0042 and 0.0055, respectively, with a tendency of higher values for the interrow conditions. Rows and interrows' emission factors were within the uncertainty range of IPCC EF for direct N_2O emission (0.0025 - 0.0225), but about 3 times lower than the default factor of 0.01 (IPCC 2006). Calculations of indirect N_2O emissions from simulated NO_3^- leaching (see section below) multiplied by the respective IPCC EF of 0.0075 (IPCC 2006) resulted in the same range as direct N_2O emissions, demonstrating their importance in particular for the given soil, climate and management conditions. Area weighted (equal coverage of rows and interrows) total field N_2O emissions increased with increasing fertilizer applications from 4.90 to 5.37 kg N_2O-N ha^{-1} yr^{-1}.

3.3.4 Nitrate leaching

Simulations of LandscapeDNDC of NO_3^- leaching were indirectly evaluated by comparing model results with measured NO_3^- concentration in soil water, since direct field measurements of NO_3 leaching were not available. Figure 3.6 shows simulated time series of NO_3 concentrations in top soil of rows (15 cm) and interrows (30 cm) compared to measured values. In general simulated and measured soil NO_3^- concentrations increased after fertilization reaching a maximum of > 200 mg NO_3-N l^{-1} approximately one month later, while decreasing to values of around 10 mg NO_3-N l^{-1} in another months time. For row conditions, simulated peak concentrations were higher than measurements, but a thorough comparison was hampered since field data unfortunately did not cover the slightly earlier timing of simulated peak concentrations. Furthermore, model simulations showed a tendency to overestimate the tailing of decreasing soil NO_3^- concentration in the lower fertilizer treatments (50 and 150 kg N). Model evaluation criteria presented in Table 3.4 demonstrate the overall capability of LandscapeDNDC to capture the temporal dynamics of soil NO_3^- concentration with r^2 values ranging between 0.3 and 0.9 and RMSPE being mostly lower than mean measured values. In addition, the magnitude of simulated soil NO_3^- concentration agreed reasonable well with field measurements, showing higher soil NO_3^-concentration in the rows as compared to interrows and a tendency of increasing values with increasing rates of N fertilizer application (Figure 3.6 and Table 3.4). Overall, mean measured and simulated soil NO_3^- concentrations during the investigation period were high but not statistically different and ranged from 53.0 to 108.0 and 91.1 to 124.7 mg NO_3-N l^{-1}, respectively.

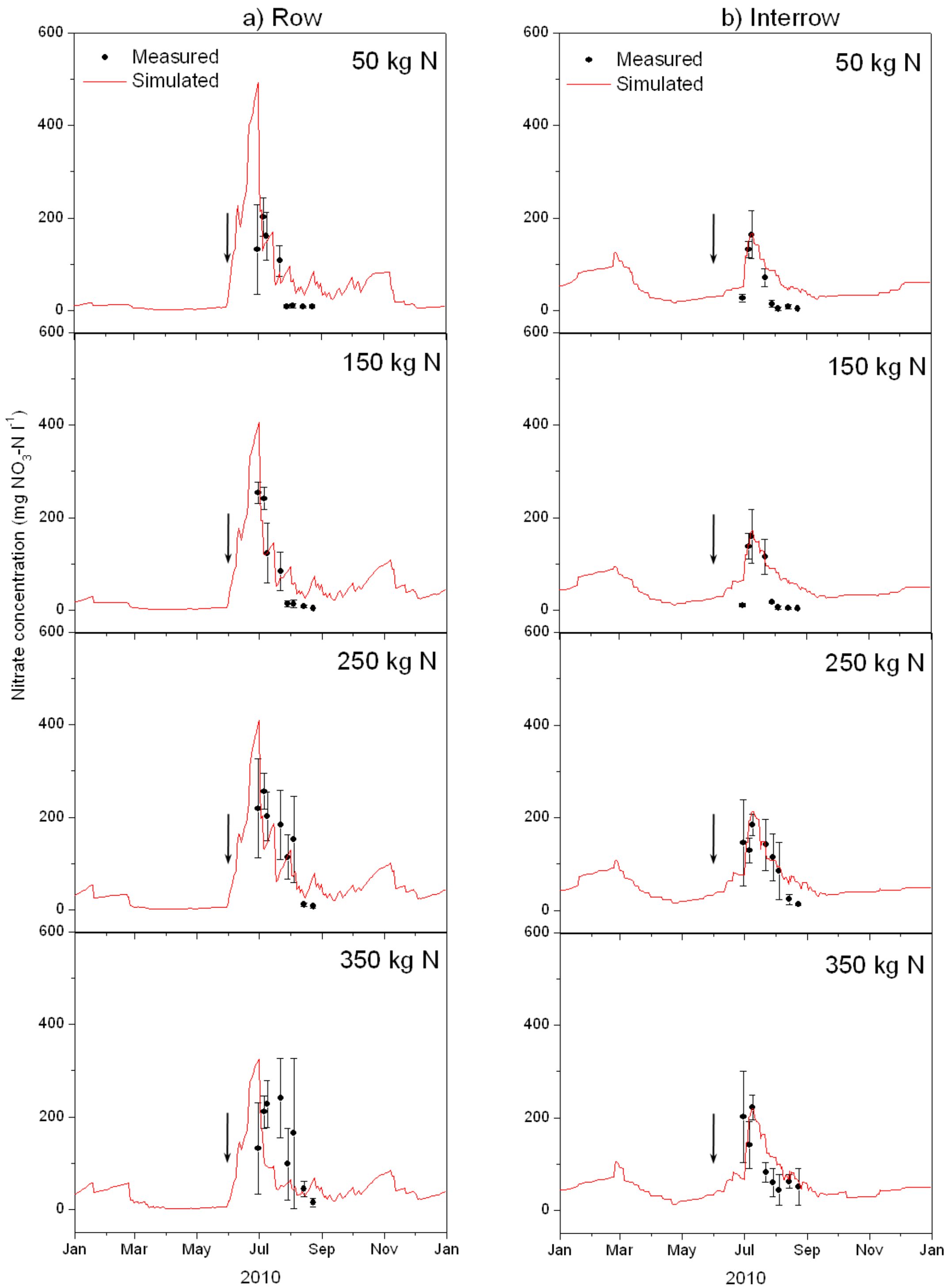

Figure 3.6 Measured (circle) and simulated (line) nitrate concentrations at a) 15 cm depth of rows and b) 30 cm depth of interrows with 50, 150, 250 and 350 kg N fertilizer treatments. Arrows indicate time and date of N fertilizer application. Bars represent standard errors of measurements

Table 3.4 Evaluation criteria of LandscapeDNDC simulations of N_2O emissions and soil nitrate concentrations of Korean radish cultivation considering different rates of N fertilization (50, 150, 250 and 350 kg N ha^{-1}). Note that N treatments have 187 kg N ha^{-1} mineral fertilizer and 228 kg N ha^{-1} of organic fertilizer addition prior to planting (details see Table 3.2). Note, Wilcoxon signed-rank test revealed no statistical difference between measured and simulated N_2O emissions and nitrate leaching of any treatment

Treatments / N_2O / Nitrate [kg N h^{-1}]	Mean		Model performance	
	Measured	Simulated	RMSPE[a]	r^2
N_2O emissions from rows [µg N m^{-2} h^{-1}]				
50	27.9±43.7	51.8±27.2	44.57	0.27
150	38.9±61.4	53.7±29.0	49.45	0.45*
250	58.8±106.8	61.3±36.3	87.28	0.44*
350	65.8±114.0	63.1±38.5	97.16	0.33
N_2O emissions from interrows [µg N m^{-2} h^{-1}]				
50	78.0±127.2	56.5±27.9	124.5	0.07
150	26.6±49.5	55.4±23.2	55.22	0.11
250	27.1±45.0	54.5±22.4	50.08	0.15
350	29.9±44.9	73.1±39.0	63.31	0.16
Nitrate concentrations from rows [mg NO_3-N l^{-1}]				
50	79.8±75.3	140.4±134.6	134.5	0.21
150	92.5±97.9	172.1±104.5	99.10	0.69*
250	143.2±86.9	132.4±107.8	95.52	0.29
350	141.6±79.1	95.47±88.2	122.9	0.01
Nitrate concentrations from interrows [mg NO_3-N l^{-1}]				
50	53.0±59.0	91.1±43.2	44.54	0.89***
150	56.8±63.8	96.9±39.1	50.05	0.89***
250	104.8±56.5	118.3±53.6	43.36	0.52*
350	108.0±66.6	124.7±56.2	64.12	0.25

[a] Root mean square prediction error
$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Table 3.5 summarizes annual values of NO_3^- leaching below the rooting zone of radish plants (60 cm soil depth) as calculated from daily simulations of LandscapeDNDC for row and interrow conditions of all fertilizer treatments. Overall, simulation results reveal very high rates of NO_3^- leaching of up to 290 kg NO_3-N ha^{-1} yr^{-1} in rows and significantly higher rates of > 400 kg NO_3-N ha^{-1} yr^{-1} in interrows without plant uptake and higher percolation rates. Annual NO_3^- leaching rates increased with increasing rates of N fertilization in rows; however, this trend was less obvious for interrow conditions (Table 3.5). The field scale area weighted (equal coverage of rows and interrows) annual NO_3^- leaching rates was about 350 kg

NO_3-N ha^{-1} for all fertilizer treatments. Figure 3.7 shows cumulative rates of NO_3^- leaching and percolation for the simulation period of 2010 for row and interrow conditions based on the 150 kg N fertilizer treatment (data from other treatments show same temporal trends). In the interrow - without plastic mulch coverage and plants - percolation and NO_3^- leaching rates started to increase one month after the fertilization, and were highly elevated for a period of about 2 months. In contrast, percolation and NO_3^- leaching rates in the row were much smaller and increased mainly 2 weeks before removal of the plastic mulch, i.e., about 2 months after the fertilization.

Table 3.5 Simulated annual N_2O emissions and nitrate leaching from 50, 150, 250 and 350 kg N fertilizer treatments. Note that all of the treatments have received additional basal fertilization of 187 kg N ha^{-1} mineral and 228 kg N ha^{-1} organic N fertilizer. Interrow -N and Field -N represent results of a scenario without fertilizing interrow. Field values were calculated as area weighted mean of row (50%) and interrow (50%)

Treatments	Direct N_2O [kg N yr^{-1}]	Indirect N_2O^a [kg N yr^{-1}]	Total N_2O^b [kg N yr^{-1}]	Nitrate leaching [kg N yr^{-1}]	EF direct N_2O^c
50 kg N ha^{-1}					
Row	2.06	1.98	4.04	264.3	0.0044
Interrow	2.37	3.39	5.76	452.3	0.0050
Interrow -N	0.78	0.15	0.93	20.4	
Field	2.22	2.68	4.90	358.3	
Field -N	1.42	1.07	2.49	142.4	
150 kg N ha^{-1}					
Row	2.16	2.07	4.23	275.8	0.0042
Interrow	2.44	3.20	5.64	426.5	0.0047
Interrow -N	0.82	0.13	0.95	17.9	
Field	2.30	2.64	4.94	351.2	
Field -N	1.49	1.10	2.59	146.9	
250 kg N ha^{-1}					
Row	2.34	2.13	4.47	283.4	0.0041
Interrow	2.46	3.15	5.61	420.0	0.0043
Interrow -N	0.83	0.14	0.97	18.2	
Field	2.40	2.64	5.04	351.7	
Field -N	1.59	1.14	2.73	150.8	
350 kg N ha^{-1}					
Row	2.38	2.18	4.55	290.0	0.0042
Interrow	3.16	3.03	6.18	403.4	0.0055

Interrow -N	0.91	0.13	1.04	17.4
Field	2.77	2.61	5.37	346.7
Field -N	1.65	1.16	2.81	153.7

[a] N_2O emissions from nitrate leaching. Indirect N_2O emissions were calculated with the IPCC`s default value, EF_5 (0.0075) (IPCC 2006)
[b] Sum of direct and indirect N_2O emissions
[c] Emission factor calculated according to IPCC (2006): N_2O emission / total N fertilization

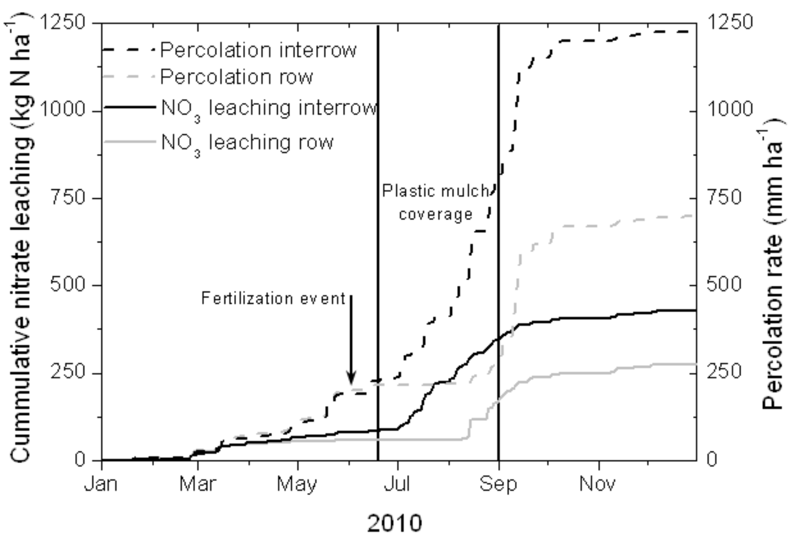

Figure 3.7 Simulated cumulative rates of nitrate leaching (solid) and percolation (dashed) in rows (gray) and interrows (black) exemplarily for the 150 kg N treatment

3.4 Discussion

Radish is one of the most important dry field crops in Korea receiving high loads of N fertilization (Cho et al. 1996; Lee et al. 2009). According to an extensive survey by the local government (Gangwon Province 2006, unpublished data) and results of a survey conducted by the TERRECO project, farmers in our study region apply on average about 588 kg N ha^{-1} up to 1000 kg N ha^{-1} to radish fields (Shope 2012, personal communication).

In this study, the LandscapeDNDC model was successfully tested against periodic field measurements and finally used for simulation of environmental impacts of Korean radish cultivation (i.e., N_2O emission and NO_3^- leaching) considering different rates of N fertilizer application. Model performance criteria were higher for nitrate leaching than for N_2O emissions (Table 3.4). To our knowledge, biogeochemical models such as LandscapeDNDC have so far not considered impacts of plastic mulch on soil environmental conditions. In a first step here, we adapted model input in order to improve simulations of soil moisture and soil temperature, the main drivers of biogeochemical soil processes. In recent years plastic mulch is of increasing importance, in particular in Asian countries like China and Korea (Jeon et al. 2011; Li et al. 2004b; Zhao et al. 2012). Several studies have reported that N_2O emissions are elevated (Nishimura et al. 2012) since mulching leads to less soil aeration, which can stimulate N_2O emissions via denitrification. However, in our study N_2O emissions from rows and interrows did not differ substantially. This is mainly due to the high sand content (> 80%) of the soil which still allowed decent aeration of the row through the plant hole in the plastic mulch. Furthermore, the LandscapeDNDC simulationssupport the contention that N_2O was mainly produced via the process of nitrification rather than denitrification due to comparable low values of anaerobic volume fraction in the top soil (10 - 60%, yearly average < 20%; data not shown), which is in agreement with Berger et al. (2013b). The main pathway of nitrogen losses was NO_3^- leaching, which can lead to indirect N_2O emissions away from the field of fertilizer application. Using the annual rates of NO_3^- leaching and the specific IPCC EF of 0.0075, our modeling study demonstrates the potentially high importance of indirect N_2O emissions from Korean radish cultivation on sandy soils in the same range as direct N_2O emissions of about 2 - 3 kg N_2O-N ha^{-1} yr^{-1}. However, it is also obvious that IPCC EFs represent global average values rather than being explicitly useful for specific agricultural cultivation systems, since the EF for direct N_2O emissions (0.0041 - 0.0055) in our study is much lower than the default value of 0.01 (IPCC 2006). It is, however, in the same range (0.0039) as reported by Xiong et al. (2006) from a radish cultivation under well aerated soil conditions. This finding makes clear that process-based biogeochemical models have a high potential to further improve (e.g. TIER 3) (IPCC 2006; Smith et al. 2010; Vries et al. 2005) estimates of N_2O emissions from agricultural productions systems, since they are able to take into account field/ regional specific climate, soil and management conditions which are finally driving biogeochemical processes responsible for soil greenhouse gas emissions. Our findings support also the recent finding of Zhou et al. (2013) that NO_3^- leaching losses can be a key factor for regulating N_2O emissions in many agricultural areas where significant amounts of NO_3^- leaching occur. LandscapeDNDC was successfully tested against field data for soil environmental conditions (temperature and moisture) and NO_3^- concentration as well as N_2O emissions for cropping of radish under plastic mulch conditions. Due to the combination of high fertilization rates (465 - 765 kg N ha^{-1}), monsoon climate with high rainfall rates in the growing season and sandy soils (> 80% sand), the investigated sites are very vulnerable to NO_3^- leaching, which is documented by simulated annual NO_3^- leaching rates of 350 kg N ha^{-1} (Table 3.5) with low variation across fertilization treatments. Soil physico-chemical properties of the site, in particular low SOC stocks resulted in low microbial biomass and activity. Regarding the high fertilization rates, not all fertilizer (ammonium-sulfate) added NH_4^+ could be transferred into NO_3^- via nitrification. For that reason, LandscapeDNDC, predicted increasing NH_4

accumulation in the soil profile with increasing fertilization rates (approx. 0, 50, 100, 150 kg N ha^{-1}), rather than varying NO_3^- leaching rates. This finding is supported by results of a survey conducted on upland fields before the cultivation season in 2011 showing soil NH_4^+ stocks of > 100 kg N. Simulated NO_3^- leaching rates > 300 kg N ha^{-1} are much higher than values reported by Cameron et al. (2013b) in a recent literature review on nitrogen losses from arable systems with maximum NO_3^- leaching rates of 155 kg N ha^{-1} yr^{-1}. and NO_3^- leaching rates reported from other vegetable cropping studies (Islam et al. 1994; McCraw and Motes 1991; Romic et al. 2003; Zhang et al. 2012). A field study of Perego et al. (2012) on maize cultivation in the Po Valley (Italy) and Sun et al. (2012) of greenhouse cultivation of cucumber in China with more comparable soil conditions to our study show similar values of NO_3^- leaching with up to > 300 kg N ha^{-1} yr^{-1}. Common of all studies is a significant increase in the fraction of NO_3^- leaching vs. N fertilization with a range of 0.1 up to 0.8, with our study resulting in 0.6 on average. Our simulation results revealed substantial higher (up to 70%) NO_3^- leaching rates in the interrows without plant uptake (> 200kg N ha^{-1}) and lower infiltration and percolation rates compared to the mulched row situation. Our modeling study also shows that highest NO_3^- leaching rates occurred after the onset of the monsoon with high rainfall events, particularly in the interrow with no plant nitrogen uptake. This finding makes clear that reducing nitrogen loss from radish cultivation under the climate and soil conditions in the Haean catchment (South Korea) must consider changes in fertilizer management. Instead of the current farmer's practice of one high application before planting, demand tailored split applications and reduced fertilization rates as already suggested by governmental recommendations (RDA 2006), or even no fertilization of the interrow, could substantially minimize NO_3^- leaching to the environment. Indeed, simulations with LandscapeDNDC assuming only fertilization of rows would reduce field scale NO_3^- leaching by 60%, and also reduce N_2O emissions by 50% (Table 3.5, Field -N vs Field).

3.5 Conclusions

LandscapeDNDC was successfully tested against field data for simulation of water content, soil temperature, crop yield, plant N uptake, NO_3^- leaching and N_2O emissions of Korean radish cultivation under plastic mulch application. Overall, model simulations revealed that with monsoon climate, sandy soils and high rates of N fertilization (465 -765 kg N ha^{-1}) NO_3^- leaching was the dominant nitrogen fate with annual leaching rates up to 350 kg N ha^{-1}. Annual field N_2O emissions (sum of direct and indirect N_2O emissions from row and interrow locations) were about 5 kg N ha^{-1}. Direct N_2O emissions would be 2-fold overestimated by use of standard IPCC EF of 1%. Since radish roots mainly grow vertically, fertilization only of rows could be an efficient mitigation strategy for significantly decreasing nitrogen losses without harming yields. Since about 50% of field N_2O emissions originate from indirect emissions, mitigating nitrate leaching will also have beneficial impacts on N_2O emissions. A further mitigation option for minimizing nitrogen losses to the environment could be reduction of soil nitrogen accumulation by cultivation of winter crops used as green manure, such as rapeseed. However, more detailed scenario analyses are necessary for improvement of farmers` practices in the study region with the aim of optimizing yields and minimizing nitrogen loads to the environment. Finally, it is still a challenge to implement the effects of plastic mulch on a more physical basis into the source code of biogeochemical models. This would also require considering nutrient and water fluxes across rows and interrows which can only be tackled by at least 2-d description of the complex field topography and linking of spatially distributed hydrological and biogeochemical models.

3.6 Acknowledgements

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Chapter 4

Estimation and mitigation of N_2O emission and nitrate leaching from intensive crop cultivation in the Haean catchment, South Korea

Youngsun Kim[1, 2], Youngho Seo[3], David Kraus[1], Steffen Klatt[1], Edwin Haas[1], John Tenhunen[2], Ralf Kiese[1,] *

[1] Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research (IMK-IFU), 82467 Garmisch-Partenkirchen, Germany

[2] Department of Plant Ecology, University of Bayreuth, 95447 Bayreuth, Germany

[3] Gangwondo Agricultural Research and Extension Services, 200-150 Gangwon Province, Republic of Korea

Abstract

Considering intensive agricultural management practices and environmental conditions, the LandscapeDNDC was applied for simulation of yields, N_2O emission and nitrate leaching from major upland crops and temperate deciduous forest of the Haean catchment, South Korea. Considering mean fertilization rates of 314 kg N ha^{-1} yr^{-1}, simulated direct N_2O emissions from crop fields cultivated with potato, radish, soybean and cabbage were 1.9 and 2.1 kg N ha^{-1} yr^{-1} in 2009 and 2010, respectively. Nitrate leaching was identified as the dominant pathway of N loss in the Haean catchment with annual mean losses of 112.2 and 125.4 kg N ha^{-1} yr^{-1}, causing threats to water quality and leading to substantial indirect N_2O emissions of 0.84 and 0.94 kg N ha^{-1} yr^{-1} in 2009 and 2010 as estimates by applying the IPCC EF_5 of 0.0075. Even under moderate to high N-deposition simulated N_2O emissions from temperate deciduous forest were low (approx. 0.50 kg N ha^{-1} yr^{-1}) and predicted nitrate leaching rates were even negligible ($\leq$ 0.01 kg N ha^{-1} yr^{-1}). On catchment scale more than 50% of total N_2O emissions originated from fertilized upland fields, only covering 27% of the catchment area. The total nitrate leaching rate was 72.0 (2009) and 59.5 (2010) t N yr^{-1}, solely (99%) stemming from fertilizer applications at upland fields. Taking into account area coverage of simulated upland crops and other land uses these numbers agree well with nitrate loads calculated from discharge and concentration measurements at the catchment outlet. The change of current agricultural management practices showed a high potential of reducing N_2O emission and nitrate leaching while maintaining current crop yields. Reducing (28 - 34%) and splitting N fertilizer application into 3 times rather than 2 times was slightly more effective and lead to about 50%

and 70% reducing of N_2O emission and nitrate leaching from the Haean catchment, the latter potentially contributing to improved water quality in the Soyang River Dam, which is the major source of drinking water for metropolitan residents.

Keywords: LandscapeDNDC, N_2O, Nitrate leaching, Water quality, Mitigation strategies

4.1 Introduction

Nitrous oxide (N_2O) is a dominant ozone depleting substance (Ravishankara et al. 2009) and one of the most important non-CO_2 greenhouse gases (GHGs) with a global warming potential 298 times higher (100-year time horizon) than that of carbon dioxide (CO_2) (IPCC 2001; Reay et al. 2012). In the global atmospheric budget agriculture soils are the strongest single source contributing approximately 58% to total N_2O emissions (IPCC 2007). In soils, N_2O originates from microbial processes of nitrification and denitrification and both processes strongly depend on soil environmental conditions and agricultural management (Butterbach-Bahl et al. 2013; Butterbach-Bahl et al. 2004; Li et al. 1992; Snyder et al. 2009).

In agriculture, nitrogen (N) fertilizer has been identified as the major source of soil N_2O emissions (Bouwman et al. 2002b; Mosier et al. 1998). Demanding about 60% of the global N fertilizer production, Asia is the largest consumer of N fertilizer (FAO 2012). Since intensive fertilizer use has been a common agricultural practice to ensure high crop yields, many countries in Asia have used N fertilizer very inefficiently (Agostini et al. 2010; Deng et al. 2011a; Min et al. 2012b). Inefficient use of N fertilizer results in low N use efficiency and enhanced N surplus in soils, which is higly susceptible to be lost as N_2O into the atmosphere and nitrate to the hydrosphere (Deng et al. 2011a; IPCC 2000; Mosier et al. 1998; Zhou et al. 2013). On a global scale, fertilizer induced N_2O emission and nitrate leaching are estimated approximately 0.8 and 19% of N fertilizer input, respectively (Bouwman et al. 2002b; FAO and IFA 2001). With regard to the world average fertilizer application of 132 kg N ha^{-1} in 2005/2007 (Alexandratos and Bruinsma 2012), South Korea utilizes about 2.5 times more fertilizer (MAFRA 2013) and is therefore classified as the country of the highest fertilizer application per hectare among OECD countries (MAFRA 2008).

The Gangwon Province accounts for approximately 63% of the total uplands (> 400 m a.s.l) in South Korea (ME 2004) and is characterized by intensive N fertilization under plastic mulch and excessive soil dressing. About 94% of these cultivated upland soils are located in the Han River Watershed, which is the main source of drinking water for 24 million metropolitan residents. According to the local survey by Gangwon Province (Gangwon-do 2006), about 60% of local farmers are applying 1.3 - 3 times more than the recommended fertilization rate, exposing high potential risks for drinking water quality (Lee et al. 2007; Shin et al. 2005b) due to significant amounts of nutrients loading to downstream during rainfall events. Previous studies showed that about 70% of the watershed NO_3-N loading could be attributed to the monsoon season with fertilized fields identified as major sources, accounting for approximately 67% of the annual watershed N loading (Deng et al. 2011a; Shin et al. 2005a).

Process-based models have been used to predict the impact of various agricultural management practices on GHG emissions and nitrate leaching by analyzing the interactions between management practices, site characteristics (e.g. climate and soil properties) and biogeochemical processes involved in ecosystem C and N cycling (Smith et al. 2010). These process-based models such as the LandscapeDNDC have been widely validated against field observations of crop growth, trace gas emissions and nitrate leaching at site scale while considering various agricultural management practices (Chirinda et al. 2011; Giltrap et al. 2008; Haas et al. 2013; Kim et al. 2014; Li et al. 2006) and have been used to estimate the regional and national inventories of crop production and GHG emissions (Cardenas et al. 2013; Haas et al. 2013; Li et al. 2001; Smith et al. 2010).

In this study, the process-based biogeochemical LandscapeDNDC model (Haas et al. 2013) was tested against field observations of N_2O emission, soil temperature and water content as well as biomass production. In the next step, the validated model was applied in a coupled model-GIS approach to estimate N_2O emission, nitrate leaching and crop yields of the Haean catchment in South Korea. Thereby, the main objectives were (1) to estimate the impacts of the intensive agricultural management on crop yields, GHG emissions and nitrate leaching, (2) to compare simulated site specific direct N_2O emission factor with the default IPCC emission factor and (3) to test the potential of mitigation strategies to reduce N loads to the environment while ensuring the current crop yield.

4.2 Materials and methods

4.2.1 Site description

The Haean catchment (38° 19' 34" N, 128°10' 25" E, 400 - 1100 m a.s.l), located in Gangwon Province, South Korea, has a total area of 61.5 km^2. Main land use is forest (59%) and upland (35%) including 8% rice paddy fields (Yanggu-gun 2012). Upland in the Haean catchment is intensively managed with a high share of potato, radish, soybean and cabbage cultivation.

The climate of Haean catchment falls under the East Asian monsoon with 13-year (1999 - 2011) annual average air temperature of 8.7°C and annual precipitation of 1617 mm with about 60% concentrated in the monsoon season (mid June - end July) (Figure 4.1). The average air temperature and the annual precipitation collected from automatic weather stations at different locations in the study region were 8.2 and 7.9°C and 1527 and 1522 mm in 2009 and 2010, respectively. The Haean catchment is one of the upstream catchments of the Soyang River Dam, which is the major source of drinking water for metropolitan residents (NIER 2012). Due to its intensive agriculture the Haean catchment contributes via the Mandae stream to the drinking water quality by high N fertilization rates in conjunction with heavy rainfall during the monsoon season. According to recent monitoring results, Total Nitrogen (TN) and Total Phosphorus (TP) concentration ranged between 3.3 - 5.3 and 0.16 - 0.96 mg l^{-1} during monsoon season in 2012, respectively (HRERC 2012). These values are far beyond the threshold of water quality standard ($\leq$ 1.5 mg l^{-1} TN and $\leq$ 0.15 mg l^{-1} TP) for inland water in South Korea (ME 2000).

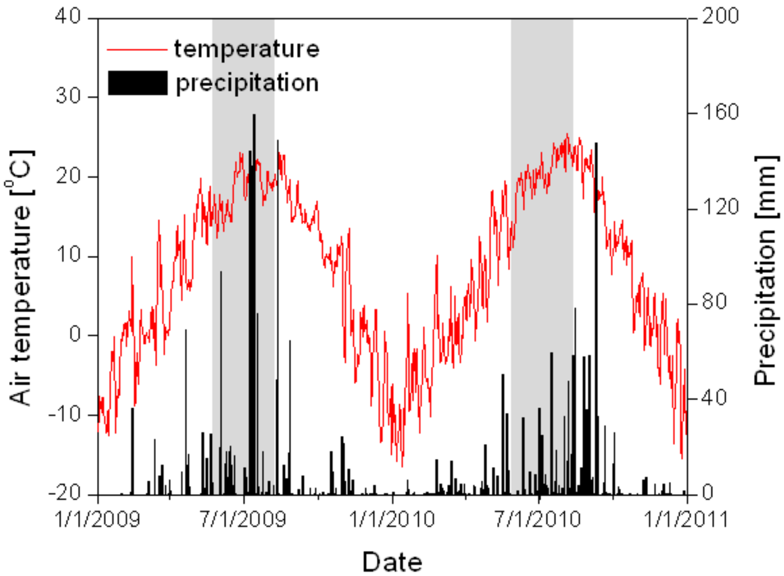

Figure 4.1 Daily average air temperature and precipitation (2009 and 2010) calculated from 12 available automatic weather stations in the Haean catchment. Gray bars represent the monsoon season

4.2.2 LandscapeDNDC model

The LandscapeDNDC model (Haas et al. 2013) used in this study is a process-based biogeochemical model integrating the agriculture-DNDC (Giltrap et al. 2010; Li et al. 1992; Ludwig et al. 2011) and the forest-DNDC (Butterbach-Bahl et al. 2009; Kiese et al. 2011; Li et al. 2000) by using a generalized soil biogeochemistry. The model is capable to simulate plant growth (arable crops and trees), biogeochemical C and N cycling and associated biosphere-atmosphere exchange of C and N trace gases (N_2O, CO_2 and CH_4) as well as nitrate leaching on daily/ subdaily time steps. The model is comprised of six major components such as air chemistry, microclimate, water cycle, soil biogeochemistry, physiology and vegetation structure. Considering various types of input data (climate, soil properties and management), the LandscapeDNDC can be run on site mode and coupled to a GIS data source also at regional and national scales (for details see Haas et al. 2013).

4.2.3 Site scale initialization and validation dataset

In a recent study of Kim et al (2014), the LandscapeDNDC model was adapted to allow simulating arable systems with plastic mulch cultivation, a main management feature in the Haean catchment with a focus on radish cultivation. Thus, simulations were preformed for row (plastic mulch) and interrow (no-mulch) conditions according to Kim et al. (2014). For purpose of further validation the LandscapeDNDC in this study was also tested against new field measurements from cabbage and potato fields operated by the Gangwondo Agricultural Research and Extension Services (Seo et al. 2013) and data from soybean cultivation (Berger et al. 2013b). Information on site properties and field management was taken from the references as well as from interviews with local farmers (Table 4.1).

Table 4.1 Soil properties and agricultural management practices of three typical crops cultivated in the Haean catchment used for site scale validation. Note that validation data of N_2O emissions and yields originated from different fields

	Cabbage		Potato		Soybean	
	Biomass	N_2O	Biomass	N_2O	Biomass	N_2O
Soil properties[a]						
Bulk density [g cm^{-3}]	1.13	1.40	1.37	1.40	1.37	1.33
SOC [%][c]	0.75	0.21	0.22	0.21	0.27	0.57
pH	5.17	6.0	6.15	6.0	5.73	5.39
Sand [%]	37.2	54	78.3	54	78.2	36
Silt [%]	48.2	18	18.3	18	18.1	50.8
Clay [%]	14.6	28	3.4	28	3.7	13.2
Stone fraction [%]	1.9		2.9		2.9	0.92
Crop management						
Seeding date [dd/mm]	28/05	29/04 26/08	27/04	29/04	27/05	15/05
Tillage date [dd/mm]	14/05 28/05	28/04 25/08	21/04	28/04	26/05	15/05
Tillage depth [m]	0.2	0.2	0.2	0.2	0.2	0.2
Basal fertilization						

Date [dd/mm]	27/05	28/04 25/08	21/04	28/04	26/05	
Type	$(NH_4)_2SO_4$	Urea	$(NH_4)_2SO_4$	Urea	$(NH_4)_2SO_4$	
Rate [kg N ha^{-1}]	145	110	300	190	24	
Additional fertilization						
Date [dd/mm]	28/05	19/05 15/09			11/06	
Type	Poultry manure	Urea			$(NH_4)_2SO_4$	
Rate [kg N ha^{-1}]	119	210			24	
Harvest date [dd/mm]	22/10	30/06 16/11	10/08	10/07	31/10	26/10

[a] cabbage and soybean (0 - 10 cm); potato (0 - 30 cm)

Due to the importance of forests in the Haean catchment, in addition to arable systems the LandscapeDNDC was also tested against field data (N_2O fluxes, soil temperature and water content) of three different forest sites (Berger et al. 2013a; Jung et al. 2014). Information on soil characteristics and dominant tree species of the forest sites located at high (950 m a.s.l), medium (650 m a.s.l) and low (450 m a.s.l) altitudes are presented in Table 4.2.

Table 4.2 Site characteristics of the three simulated forest sites

	Site A (950 m a.s.l)	Site B (650 m a.s.l)	Site C (450 m a.s.l)
Soil properties[a]			
Bulk density [g cm^{-3}]	0.87	0.78	0.88
SOC [%][c]	1.69	4.65	10.91
pH	5.09	4.54	4.78
Sand [%]	75.7	60.4	45.2
Silt [%]	19.5	30.7	42.7
Clay [%]	4.8	8.9	12.2
Stone fraction [%]	4.7	3.5	0
Dominant tree species	*Quercus Mongol.*	*Quercus Mongol.*	*Quercus Mongol.*
Basal area [m^2 ha^{-1}]	20.8	10.8	3.9
DBH [m][b]	0.06	0.07	0.10
Height [m]	4.92	9.40	9.58
Volume [m^3 ha^{-1}]	34.1	34.0	12.4

[a] 0 - 10 cm soil depth; [b] Diameter at Breast Height

4.2.4 Regional scale model input data

After site scale validation the LandscapeDNDC was used for upscaling of crop yields, N_2O emission and nitrate leaching for the Haean catchment area. For this purpose spatially distributed input data was collected and compiled in a GIS database.

Land use

Based on extensive field surveys conducted within the scheme of the TERRECO project (GRK 1565/1), polygon based land use maps were generated for the year 2009 and 2010 including different land uses such as forest, upland crops and paddy rice, orchard, seminatural and residential area (Figure 4.2) and decomposing the catchment into 1606 and 1411 polygons (agricultural and forest regions) in 2009 and 2010, respectively. The dominant land use is forest, which covers nearly 60% of the total area in the Haean catchment mainly at slopes, followed by upland crops (27.3%) including potato, radish, soybean and cabbage (Yanggu-gun 2012). Other crop fields (e.g. rice, ginseng, pepper, etc) were indicated as other land uses (10.2%) and were neglected in this study.

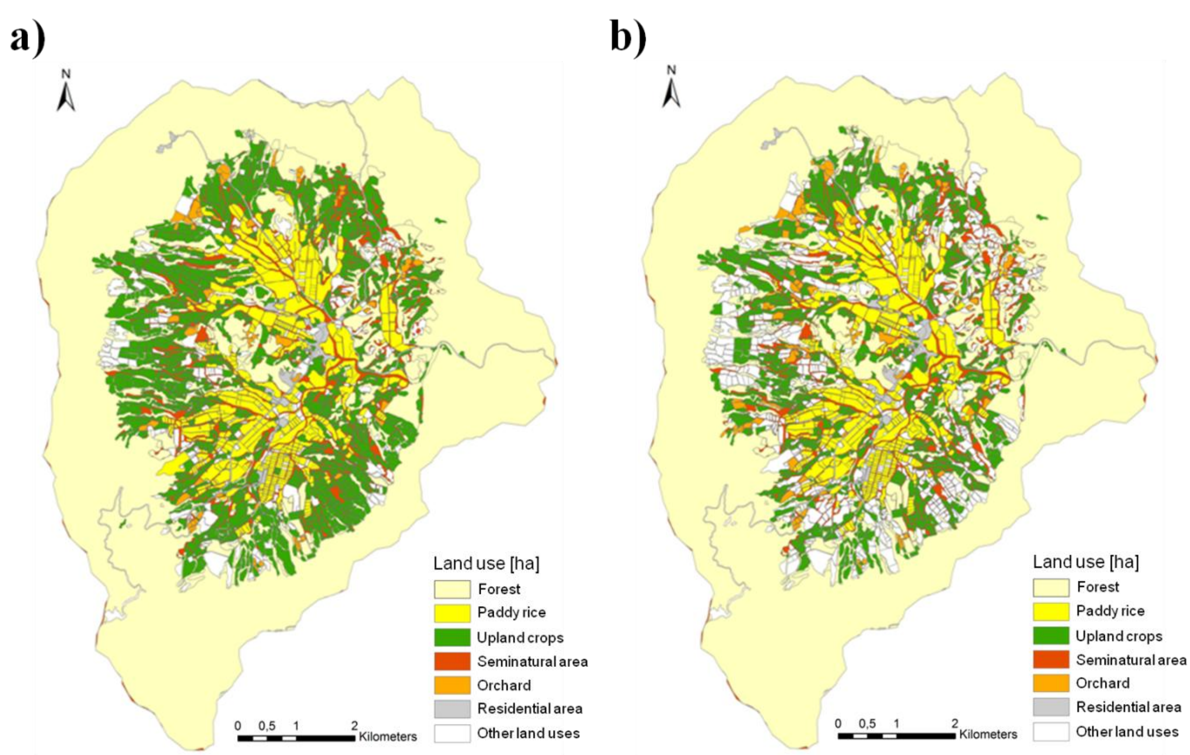

Figure 4.2 Different land uses of the Haean catchment in a) 2009 and b) 2010

Soil

The field-based soil survey was simultaneously conducted with the land use survey in 2010. The soil map is based on a digital elevation model with 30 m resolution, including 9 different types of soils classified by land use (e.g. forest, upland and rice paddy) and topography. Agricultural soils were subdivided into root-crop soils at low slope (ca. 3.6°) and non-root-crop soils at moderate slope (ca. 7.5°). Forest soils were subdivided into moderate and low slopes (ca. 12.0°) at 546 - 664 and < 546 m a.s.l, respectively with detailed soil characteristics such as soil texture, SOC, bulk density, pH, and other parameters. Root-crop soils at low slope were applied to the simulation of potato and radish fields and non-root-crop soils at moderate slope were used for the simulation of cabbage and soybean fields. Detailed information on soil properties is described in Table 4.3.

Table 4.3 Soil properties of agricultural and forest sites on different landscape positions in the Haean catchment

Land use	Slope	Depth [cm]	BD[a] [g cm^{-3}]	pH	SOC[b] [%]	Sand [%]	Silt [%]	Clay [%]	FC[c] [vol %]	WP[d] [vol %]
Agriculture	Low	0 - 30	1.39	5.8	0.5	82.4	15.1	2.5	0.41	0.04
		30 - 60	1.45	5.3	0.3	63	28.9	8.1	0.38	0.04
	Moderate	0 - 30	1.39	5.3	0.5	63.8	28.8	7.5	0.39	0.04
		30 - 60	1.55	5.1	0.7	35.6	55.3	9.1	0.36	0.03
Forest	Low and	0 - 30	0.92	4.3	6.4	43	34.7	22.3	0.54	0.12
	Moderate	30 - 60	1.12	4.4	1.0	50	30	20	0.48	0.10
		60 - 140	1.29	4.5	0.0	70	20	10	0.44	0.07

[a] Bulk Density; [b] Soil Organic Carbon; [c] Field Capacity; [d] Wilting Point

Climate

Daily meteorological data (e.g. average, maximum and minimum air temperature, precipitation, radiation, relative humidity and wind speed) was provided from 12 automatic weather stations operated at different altitudes (450 - 1050 m a.s.l) in the Haean catchment in 2009 and 2010. Each polygon was assigned to the nearest weather station with respect to its altitude by ArcGIS (version 10.0) proximity tools.

Crop management

Information on agricultural management practices of upland crops in the Haean catchment such as dates of seeding/transplanting, tilling, fertilization and harvest was provided from the survey of about 300 local farmers conducted by the TERRECO project in 2010 (Shope et al. 2014). Data on N fertilizer types and rates was not available from the survey and was therefore derived from government statistics (RDA 2010; 2011) for the simulation area. Details and timelines of agricultural management for the major upland crops simulated in this study are provided in Figure 4.3, indicating the annual fertilization rates of 68, 272, 325 and 346 kg N ha^{-1} for soybean, potato, radish and cabbage cultivation, respectively.

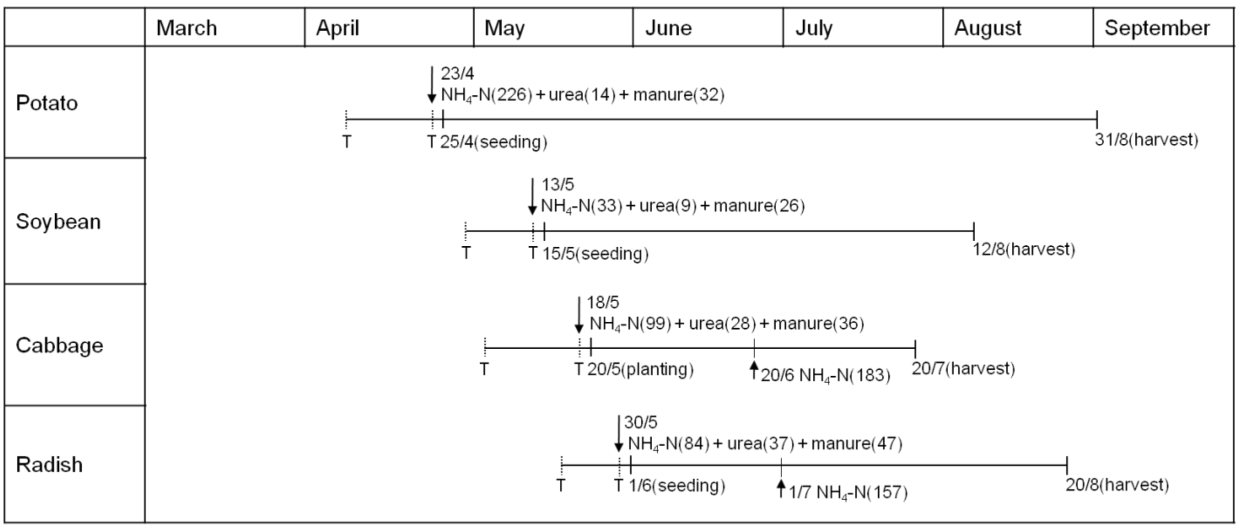

Figure 4.3 Scheme of agricultural management practices in 2009 and 2010. Note that all crops were cultivated by mulching with plastic film covering plant rows from seeding to harvest

Note:
1) Solid lines indicate seeding or harvest dates [dd/mm].
2) Dotted lines marked with T indicate the timing of tillage.
3) Arrows represent the N fertilization date.
4) Values in brackets indicate the application rates of N fertilizer [kg N ha^{-1}].

The simulation consisted of 24 different rotations e.g. combining the major upland crops including fallow years. Distribution of the rotations on to the polygons considering different soil properties and climate conditions resulted in an overall number of 204 individual simulations for the regional inventory. Note that fallow fields have not been considered to be simulated. To get the model into the equilibrium after initialization, a 2 year spin-up period was pre-added using the same management information per polygon. Rows (plastic mulch) with the modified meteorological data and interrows (no-mulch) with the measured actual weather data were separately simulated and then the average values of row and interrow simulations were taken in order to estimate N_2O emission and nitrate leaching from major upland crop fields of the Haean catchment.

For the mitigation assessment, the split fertilization into 2 or 3 times, their timings and reduction rates by up to 75% were randomly sampled by a Latin Hypercube Sampling covering the discrete space of possible management options and simulated with the LandscapeDNDC model for the regional inventories (154 for Split2 and 899 for Split3). The sampled management options leading to the optimal reduction of N_2O emission and nitrate leaching could be derived for each polygon out of the 1053 regional simulations while ensuring the current crop yield.

4.2.5 Model performance measures

The coefficient of determination (r^2), model efficiency (EF), relative mean deviation (RMD) and normalized root mean square prediction error ($RMSPE_n$) were used to evaluate the model performance (see Cui et al. 2014 and Kiese et al. 2011).

$$r^2 = \frac{\left(\sum(x_{mea} - \bar{x}_{mea})(x_{sim} - \bar{x}_{sim})\right)^2}{\sum(x_{mea} - \bar{x}_{mea})^2 \sum(x_{sim} - \bar{x}_{sim})^2} \quad (1)$$

$$EF = 1 - \frac{\sum(x_{sim} - x_{mea})^2}{\sum(x_{mea} - \bar{x}_{mea})^2} \quad (2)$$

$$RMD = \frac{1}{\bar{x}_{mea}} \sum \frac{(x_{sim} - x_{mea})}{n} \quad (3)$$

$$RMSPE_n = \frac{\sqrt{\frac{\sum(x_{mea} - x_{sim})^2}{n}}}{SD} \quad (4)$$

Where x_{mea} is the measured value, x_{sim} is the simulated value, $\bar{x}_{mea}$ is the average of field measured data and $\bar{x}_{sim}$ is the average of simulated data. SD is the standard deviation of field measured data and n is the number of values.

4.3 Results and discussion

4.3.1 Site scale model validation

Soil temperature and water content

Observations of soil temperature and water content were only available for the soybean field and the three different forest sites. Figure 4.4 shows the comparison of model simulations exemplarily for the soybean and the forest site with low sloping conditions. Row (plastic mulch) and interrow (no-mulch) simulations of the soybean field followed the procedure of adjusting meteorological input data as described in Kim et al. (2014). Seasonal dynamics and magnitude of soil temperature was captured very well, indicated by high values r^2 (0.67 - 0.93) summarized for all sites in Table 4.4. Simulation of temporal dynamics of soil water content were of lower agreement but still reasonable represented by model performance measures of r^2 ranging between 0.19 - 0.78. Generally, LandscapeDNDC was able to simulate site differences in average soil water contents ranging from 9.0±4.9 - 31.5±5.2 vol % (r^2 = 0.43) (Table 4.4).

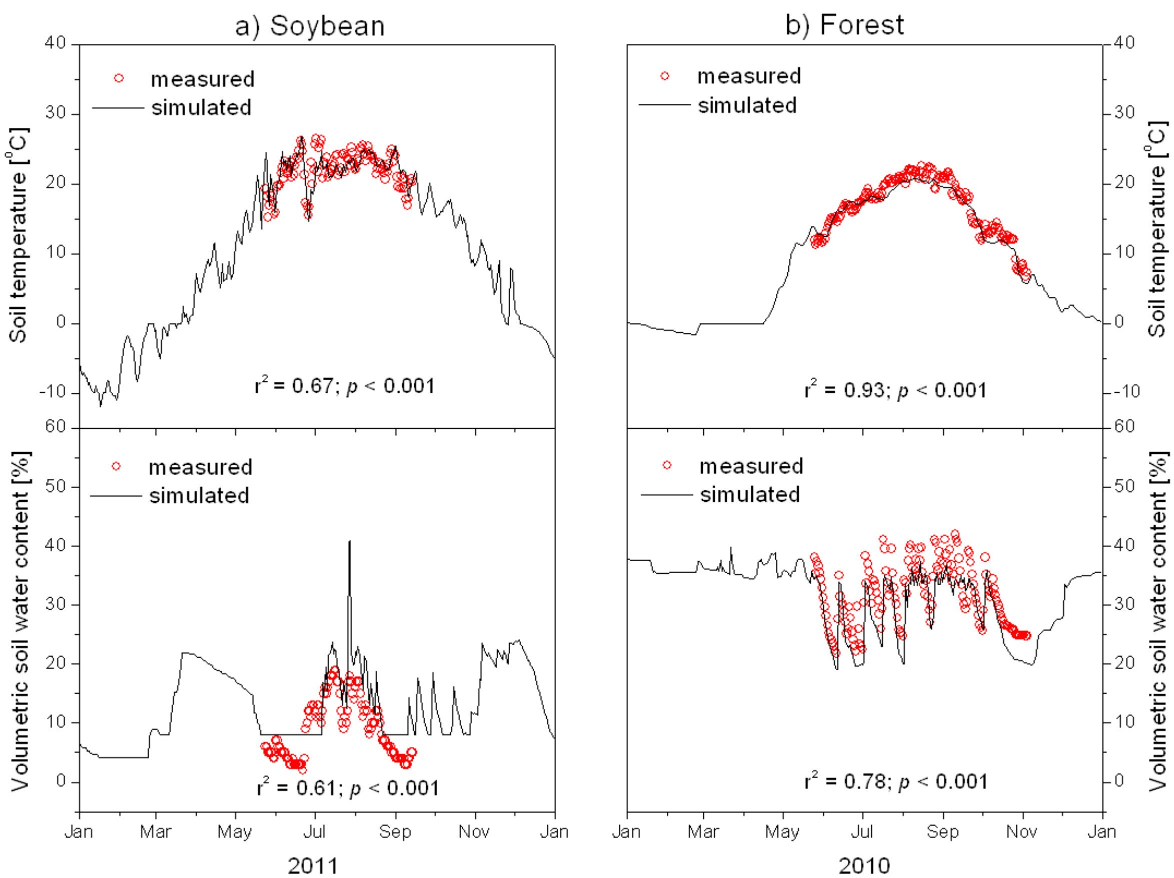

Figure 4.4 Comparison between measured (circle) and simulated (line) soil temperature and soil water content of a) a soybean and b) a forest site

Table 4.4 Evaluation of model performance for simulation of soil environmental conditions

Land use	Mean soil temperature [°C]		Model performance				Mean soil water content [%]		Model performance			
	Measurement	Simulation	r^2	ME[a]	RMD[b]	$RMSPE_n$[c]	Measurement	Simulation	r^2	ME	RMD	$RMSPE_n$
Soybean-Row	22.0±2.6	22.2±2.3	0.67***	0.66	< 0	0.58	9.0±4.9	12.5±6.5	0.61***	< 0	< 0	1.08
Soybean-Interrow	21.5±2.4	19.9±2.6	0.76***	0.30	< 0	0.83	30.2±10.8	17.8±8.0	0.19***	< 0	< 0	1.49
Forest-Site A	15.2±3.6	14.1±3.7	0.86***	0.76	< 0	0.49	27.5±1.5	27.8±2.3	0.30***	< 0	0.01	1.27
Forest-Site B	15.8±3.9	13.9±4.0	0.80***	0.53	< 0	0.69	22.5±3.5	25.5±2.5	0.25***	< 0	0.09	1.05
Forest-Site C	16.7±4.0	16.2±3.8	0.93***	0.91	< 0	0.30	31.5±5.2	28.5±5.6	0.78***	0.42	< 0	0.76

[a] Model Efficiency; [b] Relative Mean Deviation; [c] normalized Root Mean Square Prediction Error; *p < 0.05, **p < 0.01, ***p < 0.001

Upland crop yields

In LandscapeDNDC leaves and stems are included in the aboveground biomass, whereas fine and coarse roots, especially for root crops such as radish (see Kim et al. 2014) and potato, are included in belowground biomass. Simulated development of plant biomass were in good agreement with observations (r^2 = 0.84 - 0.98), even though the model slightly overestimated the aboveground biomass production at the early growing stage (Figure 4.5). Measured total biomass of cabbage, potato and soybean at the day of harvest were 0.97, 1.13 and 0.58 kg DW m^{-2} (TERRECO, unpublished data) which agreed very well with simulation results of 0.96, 1.13 and 0.56 kg DW m^{-2}, respectively.

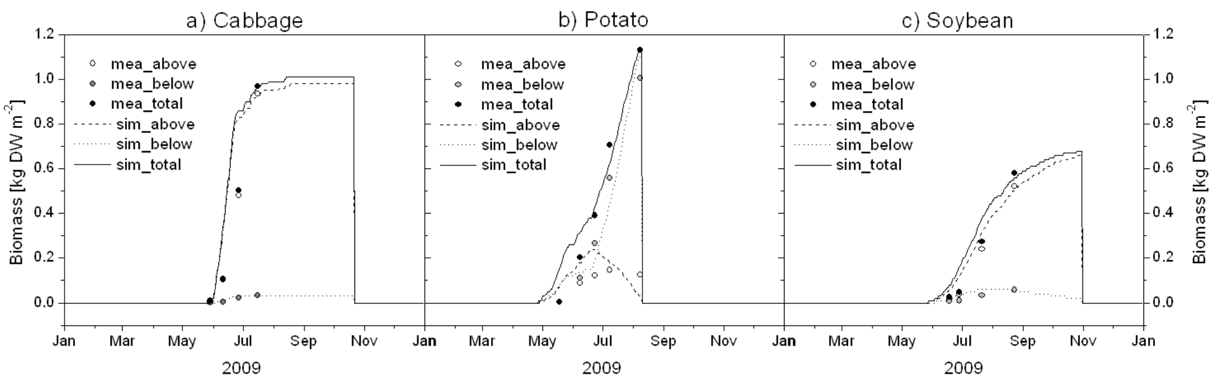

Figure 4.5 Measured (circle) and simulated (line) biomass development of a) cabbage, b) potato and c) soybean. Total biomass indicates the sum of above and belowground biomass

Our model validation compiles the evaluation of crop sequences, temporal crop growth and soil temperature and water content variables resulting in model performance measures which are comparable to other studies which focused on soil water dynamics and micrometeorology (Kröbel et al. 2010; Li et al. 2012; Perreault et al. 2013).

A recent study by Kim et al. (2014) showed the potential of LandscapeDNDC for simulating the impacts of plastic mulch on soil microclimate, N_2O emission and nitrate leaching in Korean radish fields. In this study, the LandscapeDNDC model was further tested against field data (i.e. soil temperature and water content, N_2O emission and crop biomass) of other typical crops cultivated in the Haean catchment such as cabbage, potato and soybean (Berger et al. 2013b; Seo et al. 2013) as well as data from the dominating deciduous forest soils (Berger et al. 2013a).

Soil N_2O emissions from upland crop and forest sites

Measured and simulated N_2O emissions varied depending on land uses and agricultural management practices. Mean simulated and measured N_2O emissions of arable and forest sites ranged between 2.9 - 58.0 ug N m^{-2} h^{-1} (Table 4.5). Highest deviation of mean fluxes was observed for the soybean field (Table 4.5) but simulations were still in the range of measurement uncertainty which significantly increased with the magnitude of fluxes (Figure 4.6c). Overall temporal dynamics of N_2O emissions were much higher in the fertilized arable systems (cabbage and potato) with measured and simulated peak N_2O emissions mainly following the interplay of fertilization and rainfall events (Figure 4.6).

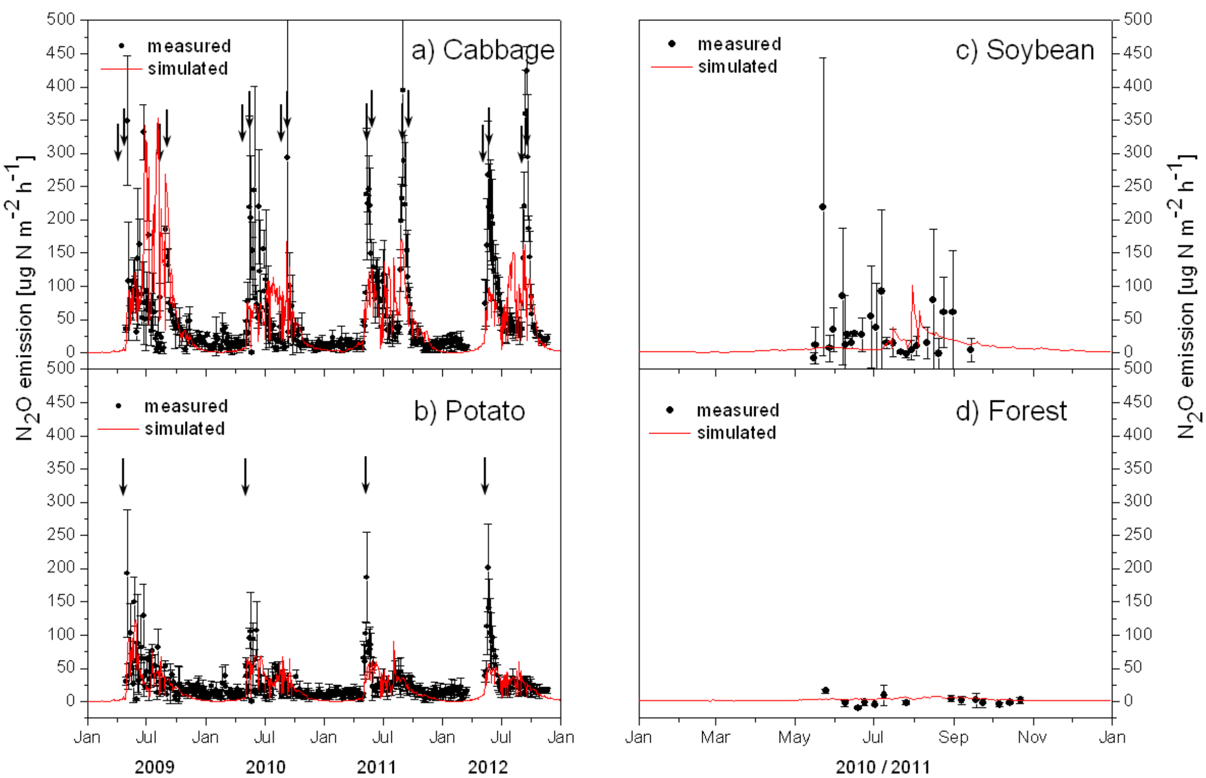

Figure 4.6 Comparison of measured (circle) and simulated (line) N_2O emissions from a) cabbage, b) potato, c) soybean and d) forest sites. Arrows indicate the dates of N fertilizer application. Bars represent standard errors of measurements

The LandscapeDNDC model did underestimate these peak emissions mainly at the first fertilization events in the cabbage and potato field. Still, simulations of daily N_2O emission patterns were of reasonable agreement (see values of model performance measures in Table 4.5, Figure 4.6), even though climate input data representing field conditions were not available and needed to be taken from the closest weather station significantly differing in elevation. Bouwman et al. (2010) demonstrated that r^2 and ME values from model studies on daily time resolution are rarely reported for N_2O because model performance is often low. Bell et al. (2012) suggested that aggregating N_2O data from daily to longer time resolutions increases the representativeness of simulated N_2O emissions. This is also the case in our study with r^2 values for daily N_2O emissions from arable soils up to 0.21 for cabbage and 0.31 for potato. Correlating means of measured and simulated N_2O emissions ($N_2O_{mea} = 0.84 * N_2O_{sim}$) revealed a much higher values of model performance measures i.e. $r^2 = 0.92$ and ME = 0.88, indicating the capability of LandscapeDNDC to represent site differences very well. This finding is supported by a recent study with LandscapeDNDC being successfully applied for simulation of N_2O emissions and nitrate leaching from radish cultivation in the Haean catchment (Kim et al. 2014). Overall, simulation performance of LandscapeDNDC is highly comparable to other modeling studies focusing on plant growth, soil water and temperature dynamics as well as N_2O emission of arable systems worldwide (e.g. CERES-EGC: Lehuger et al. 2010; DAYCENT; Smith et al. 2008; Abdalla et al., 2010; DNDC: Deng et al. 2013; ECOSSE: Bell et al., 2012; Khalil et al. 2013; FASSET: Chirinda et al. 2011; STICS: Jégo et al., 2010; RIWER Jing et al. 2010), which further evidences the robustness of LandscapeDNDC to simulate typical Korean (i.e. Southeast Asia) agricultural systems.

Dynamics and magnitude of measured and simulated N_2O emissions from the three forest sites were much lower as compared to the arable sites (Figure 4.6 and Table 4.5) with simulated N_2O emissions slightly underestimating measured values. These deviations were mainly due to sporadic uptake of atmospheric N_2O by forest soils, which cannot be simulated by the current version of LandscapeDNDC, yet. This limitation was one of the main reasons for the rather poor values of model performance for daily comparison of forest simulations (Table 4.5).

The capability for simulating of C and N turnover and associated losses such as N_2O and nitrate is further supported by more studies of successful LandscapeDNDC applications and earlier model versions for other arable and forest ecosystems worldwide (Cui et al. 2014; Haas et al. 2013; Kiese et al. 2011; Kim et al. 2014; Kraus et al. 2015; Werner et al. 2007), indicating that LandscapeDNDC is generally capable to be used also in the framework of up-scaling procedures from site to regional/ catchment scale.

Table 4.5 Evaluation of model performance for simulation of N_2O emissions from major upland crop fields and forest sites

Land use	Mean N_2O emission [ug N m^{-2} h^{-1}]		Model Performance			
	Measurement	Simulation	r^2	ME[a]	RMD[b]	$RMSPE_n$[c]
Cabbage	58.0±80.4	54.3±62.2	0.21***	0.11	< 0	0.94
Potato	27.1±27.6	21.7±22.1	0.31***	0.21	< 0	0.89
Soybean-Row	16.5±24.3	5.7±7.5	< 0.1	< 0	< 0	1.15
Soybean-Interrow	34.7±46.1	14.9±11.5	< 0.1	< 0	< 0	1.16
Forest-Site A	0.35±3.59	3.27±1.16	< 0.1	< 0	8.38	1.34
	(2.89±2,82)[d]	(3.53±1.34)	0.46	< 0	0.22	1.39
Forest-Site B	-1.25±5.89	4.94±1.50	0.18*	< 0	< 0	1.40
	(4.30±2.34)	(6.07±1.43)	0.1	< 0	0.41	1.29
Forest-Site C	0.55±6.08	4.09±1.53	< 0.1	< 0	6.48	1.13
	(5.87±5.31)	(4.75±1.57)	< 0.1	< 0	< 0	1.09

[a] Model Efficiency; [b] normalized Root Mean Square Prediction Error; [c] Relative Mean Deviation
[d] Values in brackets indicate N_2O emissions, except for N_2O uptake by forest soils
*p < 0.05, **p < 0.01, ***p < 0.001

4.3.2 Regional scale model application (Haean catchment)

Upland crop yields

Regional biomass production agreed well with observation of cabbage, potato and soybean yields as reported from the TERRECO project (unpublished data) and national statistics (Yanggu-gun 2009; 2010). Due to favored climate conditions with higher temperatures the LandscapeDNDC predicted generally higher mean yields for the specific crops in 2009 as compared to 2010 (Table 4.6).

N_2O emission

Simulated direct N_2O emission in 2009 and 2010 ranged between 1.17 - 2.78 kg N ha^{-1} yr^{-1} with mean values of 1.92 and 2.14 kg N ha^{-1} yr^{-1}, respectively (Table 4.6). Figure 4.7a shows the regional distribution of simulated direct N_2O emissions from the Haean catchment exemplarily for 2010 with N_2O emissions mainly represented by orange to red colors (green colors represent forest sites). In 2009, the highest direct N_2O emission was predicted for radish fields with a mean value of 2.78 kg N ha^{-1} yr^{-1}, followed by potato and cabbage fields. This sequence was different in 2010 with highest mean emissions for radish fields (2.77 kg N ha^{-1} yr^{-1}) > cabbage > potato. Overall, lowest N_2O emissions were predicted for non-fertilized soybean fields with 1.17 and 1.29 kg N ha^{-1} yr^{-1} in 2009 and 2010, respectively (Table 4.6).

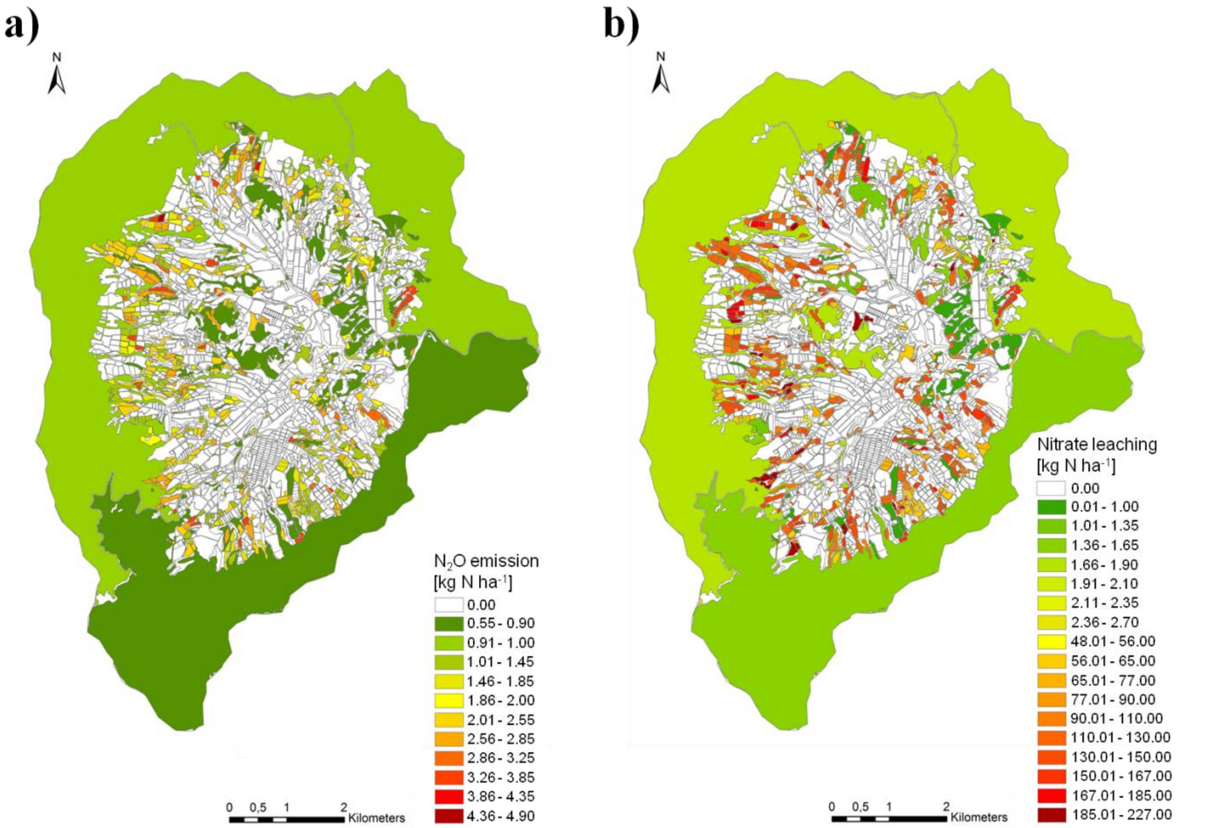

Figure 4.7 Spatial variability of simulated a) direct N_2O emissions and b) nitrate leaching rates from major upland crop fields and temperate deciduous forest of the Haean catchment in 2010

For calculation of N_2O emission factors (EF_d), model simulations were compared with N_2O emissions (data not shown) from 0-N fertilizer simulations. EF_d ranged between 0.54 - 1.09 and 0.59 - 1.22% in 2009 and 2010, respectively (Table 4.6), which is within the uncertainty range EF_d (0.3 - 3%) summarized by IPCC (IPCC 2006). N_2O EF_d of radish and soybean fields were slightly higher than the IPCC`s default value of 1.0% (IPCC 2006), whereas EF_d of cabbage and potato fields showed much lower values. Indirect N_2O emissions were estimated by applying the IPCC EF_5 of 0.0075 (IPCC 2006) to simulated nitrate leaching rates and ranged between 0.53 - 1.14 kg N ha^{-1} yr^{-1} in the two years simulated with highest values found for cabbage and radish fields (Table 4.6). Due to high rates of nitrate leaching (see next section indirect N_2O emissions from crop production in the Haean catchment are more than significant and contribute about 30.3% to total (direct and indirect) N_2O emissions (Table 4.6). The highest total N_2O emission with values up to 4 kg N ha^{-1} yr^{-1} was estimated for the radish cultivation.

Regression analysis of total catchment simulations revealed that N_2O emissions mainly correlated with rates of N fertilization and less with soil (sand content) and climate (precipitation) conditions (Table 4.7), which showed only minor spatial variation (Table 4.3). In relation to the high fertilization rates (catchment average: 314 kg N ha^{-1} yr^{-1} neglecting soybean cultivation), direct N_2O emissions were low to moderate (1.17 - 2.78 kg N ha^{-1} yr^{-1}) which is also reflected by values of N_2O EF_d mostly lower than the IPCC default (Table 4.6). These results are comparable to N_2O emissions and N_2O EF_d reported for similar intensively managed agricultural systems in Southeast Asia (Min et al. 2012a; Zhou et al. 2013).

Simulations of N_2O emissions from temperate deciduous forest sites ranged between 0.35 - 0.65 kg N ha^{-1} in the two years simulated. Predicted annual mean N_2O emissions were 0.51 and 0.50 kg N ha^{-1} in 2009 and 2010, respectively. Slightly higher N_2O emissions were estimated for the moderate slope as compared to the low slope soil conditions (Table 4.6). Due to very low rates of nitrate leaching (< 0.01 kg N ha^{-1} yr^{-1}), indirect N_2O emissions of the forest ecosystems were negligible. Even though intensive agriculture in the Haean catchment leads to elevated atmospheric N deposition (24 - 51 kg N ha^{-1} yr^{-1} reported by Berger et al. 2013a), simulated N_2O emissions of forest ecosystems in the Haean catchment are still low (< 1 kg N ha^{-1} yr^{-1}) and did not correlate with the magnitude of atmospheric N deposition. Previous studies have revealed different results when correlating N deposition and N_2O emission from forest soils which were significant (Kesik et al. 2005) or not significant (Ambus and Robertson 2006; Pilegaard et al. 2006). In our young (50 - 60 years old) temperate deciduous forest stands this might be attributed to the significant plant N uptake (simulated yearly average: 68.2 kg N ha^{-1}, data not shown) to sustain the tree growth.

The estimation of the total N_2O emissions from the Haean catchment (sum of the total N_2O emissions from agricultural and forest regions) was lower in 2010 (2.93 t N yr^{-1}) than in 2009 (3.31 t N yr^{-1}) mainly due to a decrease of agricultural cropping area (-23%) and thus total amounts of N fertilization (-28%) (Figure 4.2). Even though the temperate deciduous forest covers approximately 59% of the total area of the Haean catchment, more than half of estimated total N_2O emission was derived from the fertilized upland fields (27% of the catchment area) through 2009 - 2010.

Nitrate leaching

Simulated nitrate leaching rates ranged between 48.9 - 166.2 (mean 112.2) and 52.8 - 226.6 (mean 125.4) kg N ha^{-1} in 2009 and 2010, respectively. Figure 4.7b shows the regional distribution of simulated nitrate leaching from major upland crops exemplarily for the year 2010. In general, nitrate leaching rates positively correlated with N fertilization rates (Table 4.7), thus higher nitrate leaching rates were simulated for cabbage, radish and potato fields (> 100 kg N ha^{-1} yr^{-1}) compared to much lower rates (< 75 kg N ha^{-1} yr^{-1}) were much lower in fields cultivated with soybean (Table 4.6). As shown for N_2O emissions including other parameters such as sand content and precipitation did hardly improve the prediction capacity of more complex regression models (Table 4.7). Compared to arable simulations the LandscapeDNDC predicted insignificant (≤ 0.01 kg N ha^{-1} yr^{-1}) rates of nitrate leaching from the temperate deciduous forest sites. Overall, predicted total nitrate leaching from the Haean catchment (sum of nitrate leaching from agricultural and forest regions) was 72.0 and 59.5 t N yr^{-1} in 2009 and 2010, respectively, with approximately 99% of the total nitrate leaching originating from upland crop fields (Table 4.6, Figure 4.7b). Studies on nitrate leaching considering other crop types (e.g. corn, oilseed rape and winter wheat), soil and climate conditions (Engström et al. 2011; Gehl et al. 2006; Sieling and Kage 2006) identified the decomposition of crop residues after harvest as a significant source of nitrate leaching beside N fertilizers. In this study, the majority of the plant biomass was removed thus, nitrate leaching was mainly caused by excess N from the basal and additional fertilizer applications.

Simulated annual nitrate leaching rates from upland fields in the Haean catchment were 72.0 t N yr^{-1} in 2009 and 59.5 t N yr^{-1} in 2010 which is 51.4 and 58.9% of applied N fertilizer in 2009 and 2010, respectively. Thus, nitrate leaching was the main pathway of N losses in the intensively cultivated Haean catchment, which is in agreement with results of previous studies, showing also high vulnerability of nitrate leaching under sandy soils and intensive N fertilization regimes (Fan et al. 2010; Hu et al. 2008). Taking into account that in this study regional simulations covered about 86% of the Haean catchment area, LandscapeDNDC estimated total nitrate leaching rates were quite similar to NO_3-N loadings calculated (concentration * discharge) at the catchment outlet of the Mandae stream, which were 89.9 and 81.5 t N yr^{-1} in 2009 and 2010 (Eum 2015), respectively.

Table 4.6 Regional simualtion of annual crop biomass, N_2O emission and nitrate leaching from the Haean catchment

Land use	Year	Biomass [t DW ha^{-1}]	Nitrate leaching [kg N ha^{-1}]				Direct N_2O [kg N ha^{-1}]				Indirect N_2O [kg N ha^{-1}][b]				Total N_2O [kg N ha^{-1}][c]				N_2O EF_d [%][d]
			mean	P25[a]	P50	P75	mean	P25	P50	P75	mean	P25	P50	P75	mean	P25	P50	P75	
Cabbage	2009	11.0	135	111	132	150	1.85	1.69	1.85	1.88	1.01	0.84	0.99	1.13	2.86	2.48	2.86	3.00	0.61
	2010	11.0	150.5	115.9	139.9	155.1	2.59	2.15	2.39	2.71	1.13	0.87	1.05	1.16	3.72	3.06	3.45	4.20	0.93
Potato	2009	17.8	111.6	102.8	109.5	120.9	1.87	1.71	1.9	2.01	0.84	0.77	0.82	0.91	2.71	2.48	2.72	2.89	0.54
	2010	14.8	129.2	114	120.2	142.8	1.92	1.79	1.84	1.94	0.97	0.86	0.9	1.07	2.89	2.6	2.78	3.16	0.59
Radish	2009	6.4	127.3	122.1	129.1	136.2	2.78	2.53	2.8	2.92	0.96	0.92	0.97	1.02	3.74	3.43	3.79	3.91	0.95
	2010	5.5	151.4	134.7	143.3	156.9	2.77	2.52	2.66	2.9	1.14	1.01	1.07	1.18	3.91	3.56	3.67	4.16	1.03
Soybean	2009	6.3	74.7	57.9	61.5	82.3	1.17	1.1	1.16	1.23	0.56	0.43	0.46	0.62	1.73	1.53	1.62	1.84	1.09
	2010	5.8	70.4	58.2	63.3	67.3	1.29	1.21	1.24	1.29	0.53	0.44	0.47	0.51	1.82	1.63	1.72	2.04	1.22
Forest-Moderate	2009		0.00				0.62	0.61	0.62	0.63					0.62	0.61	0.62	0.63	
	2010		0.01				0.60	0.59	0.61	0.62					0.60	0.59	0.61	0.62	
Forest-Low	2009		0.00				0.40	0.39	0.40	0.41					0.40	0.39	0.40	0.41	
	2010		0.00				0.39	0.39	0.40	0.40					0.39	0.39	0.40	0.40	

[a] Percentile values

[b] N_2O emissions from nitrate leaching were calculated with the IPCC default value of 0.0075 (IPCC 2006)

[c] Sum of direct and indirect N_2O emissions

[d] Direct N_2O emission factors for applied N fertilizer: EF_d [%] = 100 x (N_2O emission from fertilized field - N_2O emission from unfertilized field) / applied N fertilizer

Table 4.7 Regression analysis of N_2O emission and nitrate leaching

Model	N_2O emission					Nitrate leaching				
	r	r^2	Adjusted r^2	Std error of the estimate	r^2 change	r	r^2	Adjusted r^2	Std error of the estimate	r^2 change
1[a]	0.76	0.57	0.26	0.54	0.57	0.92	0.85	0.73	16.14	0.85
2[b]	0.75	0.56	0.39	0.49	-0.01	0.91	0.82	0.75	15.71	-0.03
3[c]	0.73	0.53	0.45	0.47	-0.04	0.88	0.77	0.73	16.14	-0.05

[a] Fertilizer, Precipitation and Sand content
[b] Fertilizer and Precipitation
[c] Fertilizer

4.3.3 Assessment of mitigation strategies

The effects of mitigation strategies (Split2 and Split3) on N_2O emission and nitrate leaching from major upland crops of the Haean catchment compared to current farmers` practices in 2009 and 2010 are presented in Figure 4.8.

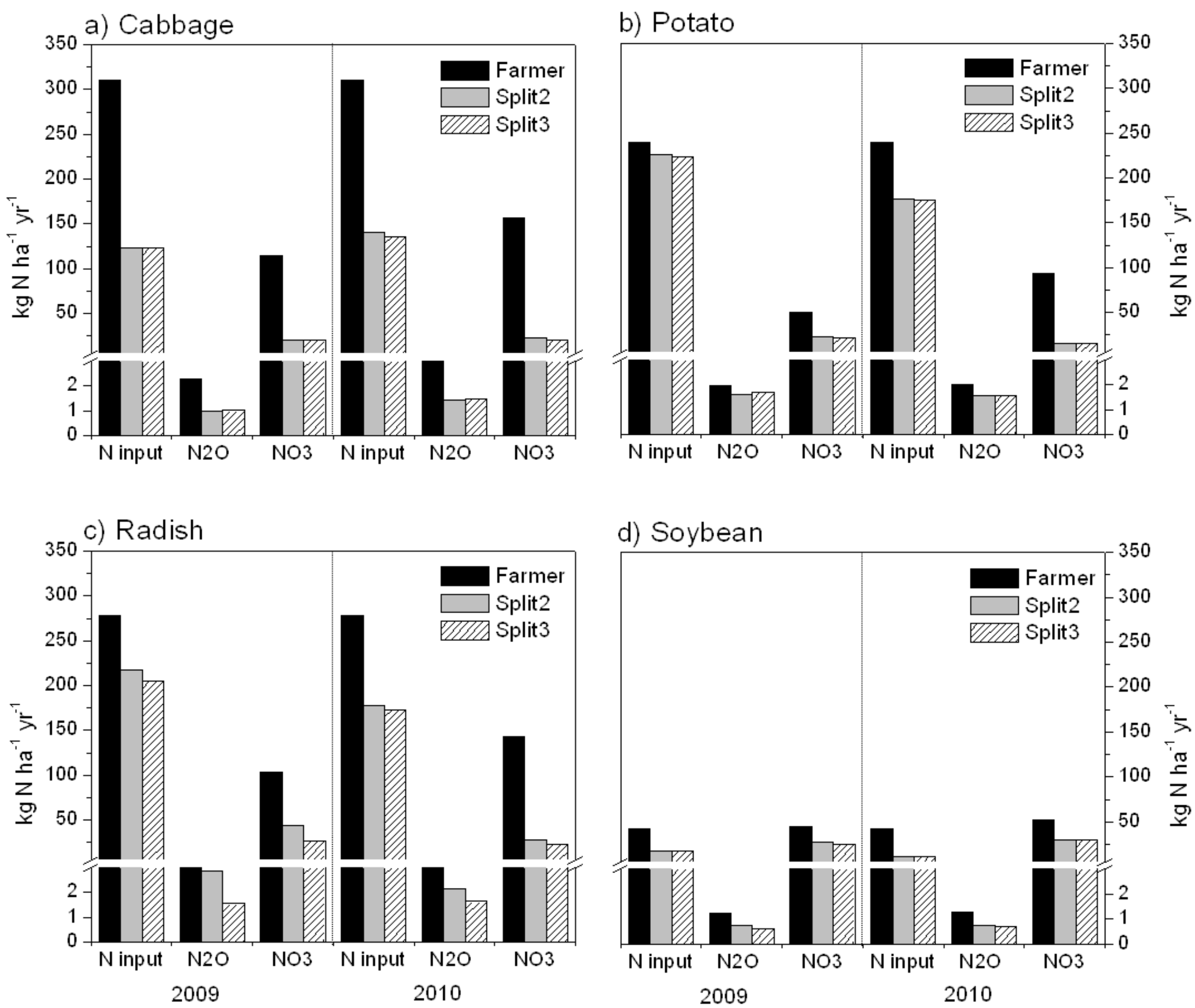

Figure 4.8 Comparison of fertilization rates, N_2O emissions and nitrate leaching from a) cabbage, b) potato, c) radish and d) soybean fields considering current farmers` practices and optimized agricultural management

Overall, Split2 and Split3 resulted in significant lower fertilization rates (-16 - -209 kg N ha^{-1} yr^{-1}), in particular for cabbage and radish and less for potato and soybean cultivation. The reduction in fertilization rates in combination with optimized application dates (Figure 4.9) significantly decreased nitrate leaching (17 - 137 kg N ha^{-1} yr^{-1}) and N_2O emissions (0.3 - 2.1 kg N ha^{-1} yr^{-1}) in all cropping systems (Figure 4.8). Further splitting fertilization from 2 into 3 applications was most effective for radish cultivation but of lower value for reduced N loads to the environment for other crops. Nevertheless, regarding the whole cropping area of the Haean catchment mitigation effects of Split3 were slightly higher as compared to Split2 and resulted in a reduction of N_2O emission by 49 and 52% and nitrate leaching rates by 68 and 78% in 2009 and 2010 (Table 4.8).

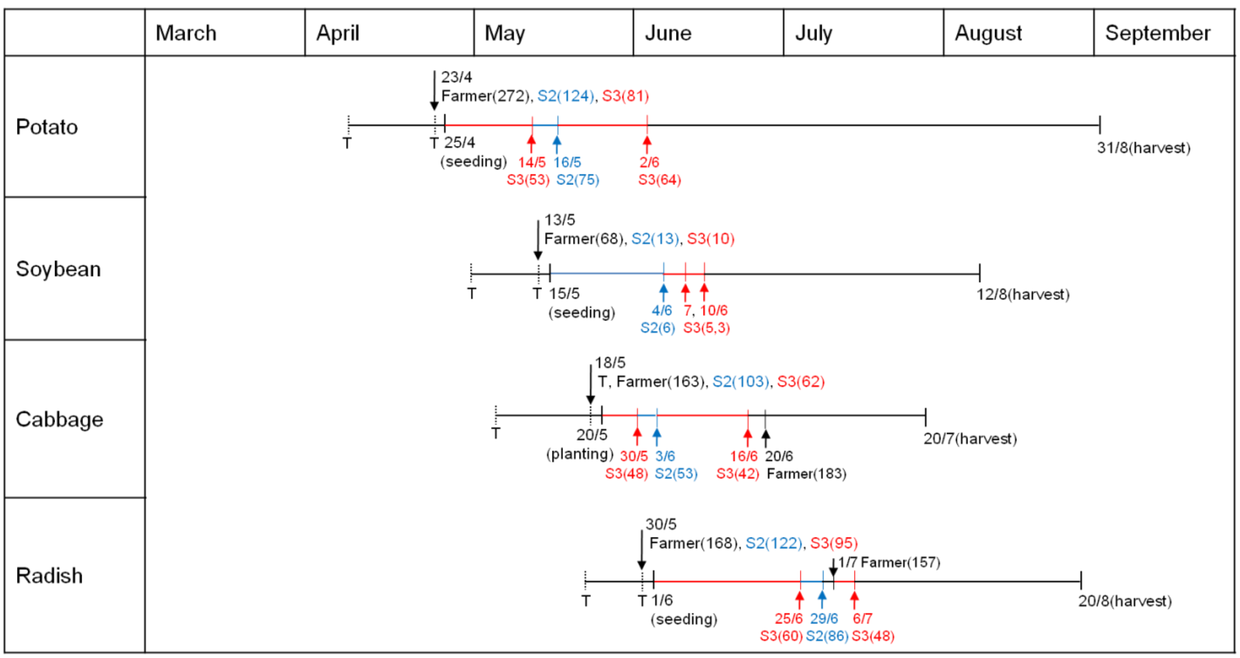

Figure 4.9 Comparison between current farmers` practices and optimized agricultural management for major upland crop cultivation in the Haean catchment

Note:
1) Solid lines indicate seeding or harvest dates [dd/mm].
2) Dotted lines marked with T indicate the timing of tillage.
3) Arrows represent the N fertilization date.
4) Values in brackets indicate the application rates of N fertilizer [kg N ha^{-1}].
Instead of indicating each application rate of NH_4-N, urea and manure (e.g. Figure 4.3), the sum of these rates were presented for the simple comparison between farmers` practices and mitigation strategies in 2010.

Reduced nitrate leaching totals in values of 30 - 40 t N yr^{-1} which would significantly decrease mean nitrate concentrations in the Mandae stream from currently 3.5 to about 2 mg l^{-1}, which is much closer to the South Korean quality standard for inland waters of 1.5 mg l^{-1}. Compared to other studies our reduction potentials for N_2O emissions and nitrate leaching are in the upper range. Deng et al. (2013) demonstrated that a 75% reduction of N fertilization would result in a 31% lowering of N_2O emissions from intensively managed Chinese vegetable fields without penalizing yields. Arregui and Quemada (2006) reported about 57.7% reduced nitrate leaching rates for fertilizer split application as compared to one single application in barley fields. Considering similar changes in agricultural management in potato fields Burton et al. (2008) and Zebarth et al. (2012) showed about 25 and 39.5% reduced N_2O emissions, respectively.

Table 4.8 Mitigation potential of N_2O emission and nitrate leaching from major upland crop fields of the Haean catchment

Year	Practice	Fertilization rate [t N yr^{-1}]	N_2O emission [t N yr^{-1}]	Nitrate leaching [t N yr^{-1}][b]
2009	Split2[a]	-43 (26)[c]	-0.64 (34)	-29.0 (60)
	Split3[b]	-46 (28)	-0.93 (49)	-32.7 (68)
2010	Split2	-46 (40)	-0.71 (47)	-38.8 (77)
	Split3	-47 (41)	-0.78 (52)	-39.5 (78)

Note that values are differences between mitigation strategies and current farmers` practices
[a] Split fertilizer application into 2 times
[b] Split fertilizer application into 3 times
[c] Values in brackets indicate the reduction rate [%] compared to the current farmers` practices

4.4 Conclusions

In this study, the biogeochemical LandscapeDNDC model demonstrated its capability for predicting crop yields, N_2O emission and nitrate leaching at site and catchment scale considering different agricultural management practices and environmental conditions. Estimated high nitrate leaching and N_2O emissions from fertilized upland fields of the Haean catchment demonstrated the urgent need to develop strategies for mitigating N exports to the environment. Reduction in N fertilization rates and adopting numbers and timing of fertilizer applications proofed to be most suitable to significantly reduce N_2O emissions and nitrate leaching without penalizing yields.

The results of this study could be used to guide improvement of current farmers` practices in order to reduce environmental impacts of crop cultivation in the Haean catchment such as water quality issues in the Soyang River Dam a downstream drinking water reservoir. However, further studies should consider other mitigation options such as cover crops (e.g. rapeseed and winter wheat) and reduced tillage both potentially contributing also to increase of soil carbon stocks and soil fertility. Up to now mitigation options were evaluated retrospectively based on observed climate data. In particular, under monsoon climate conditions, application of process-based models such as the LandscapeDNDC linked to prediction of actual weather forecast data (4 weeks) could further help to define optimal timing and rates of fertilization as well as seeding and planting of crops.

4.5 Acknowledgments

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