Evaluation of NO₃-N Leaching in Commercial Fields of Leafy Vegetables by the Soil Nitrogen Balance Estimation System

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Nitrate-N (NO₃-N) leaching in intensive crop production systems is an important issue due to its potential as a pollutant and a valuable resource. This study aimed at evaluating NO₃-N leaching using on-farm measurements and modeling of 12 commercial fields of leafy vegetables characterized by an array of farm management. Real-time monitoring of the soil moisture, temperature and bulk electrical conductivity using a capacitance/resistance sensor was carried out to verify the temperature index and the leaching constant integrated in the soil nitrogen balance estimation system. Results showed that measured soil temperature strongly correlated to model estimates. Values of the leaching constant were 0.0006 kg kg⁻¹ and 0.00075 kg kg⁻¹ (in 2013) both of which were close to the model value of 0.0007 kg kg⁻¹. Values in 2012 were either too high (0.00127 kg kg⁻¹) or too low (0.0010 kg kg⁻¹). NO₃-N leaching ranged from 13.50 kg ha⁻¹ to 72.71 kg ha⁻¹ in 2012 and 8.66 kg ha⁻¹ to 41.10 kg ha⁻¹ or 0.00 kg ha⁻¹ to 41.10 with or without rye, respectively. NO₃-N leaching in single cropping systems of 2012 was higher than in double cropping systems of 2013.

Keywords : capacitance/resistance sensor, FAO reference evapotranspiration, leaching, NO₃-N, soil N balance estimation system

INTRODUCTION

Nitrogen (N) is one of the most important element limiting nutrients for plant growth and one of the largest energy-input in agricultural production systems is through N fertilizers. Intensive crop production involves the application of inorganic and organic N fertilizer forms to supplement the soil resource base (Christian and Riche, 1998). Over-fertilization and inappropriate timing of fertilizer application may enrich soil water with nitrate-N (NO₃-N) (Christian and Riche, 1998) and result to NO₃-N leaching that is economically and environmentally undesirable (Asadi and Clemente, 2003; Luce et al., 2011). Several strategies of managing soil N that may reduce or prevent NO₃-N leaching in intensive crop production systems have been proposed and experimented (Horiuchi, 2001; Di and Cameron, 2002; Qiaogang et al., 2008; Zupanc et al., 2011). However, in intensive leafy vegetable production systems, excessive application of N in the form of chemical fertilizers to achieve maximum yield per cultivated area is usually accompanied by NO₃-N leaching (Mishima, 2001).

NO₃-N leaching below the rooting zone results to point and non-point-source pollution and high cost-benefit ratio of agricultural production are sustainability issues that

have been addressed for decades (Kumazawa, 1999; Maeda et al., 2003; Bergström et al., 2005; Schoolman et al., 2011). NO₃-N leaching has been evaluated using lysimeters (Ogawa et al., 1979; Kobayashi et al., 1995; Suzuki and Shiga, 2004), porous ceramic cups (Williams and Lord, 1997; Christian and Riche, 1998), ion-exchange-resin cartridges (Predotova et al., 2011) and well calibrated computer models. Traditionally, a technique for monitoring salts in the soil of which NO₃-N is not exempted involved core sampling (Patriquin et al., 1993; Eigenberg et al., 2002) or the use of suction probes (Williams and Lord, 1997; Christian and Riche, 1998) and subsequent laboratory analyses. Monitoring solutes in the soil has evolved through destructive and a series of non-destructive methods whose applicability is dependent upon the study objectives. Soil resistivity techniques such as resistance probes, low frequency capacitance probes (Aimrun et al., 2009; Scudiero et al., 2012), time-domain reflectometry (Payero et al., 2006; Krishnapillai and Ranjan, 2009; Persson and Dahlin, 2010), soil water samplers (Higashi et al., 2005), tracers (Shibano and Ohno, 1988) and morphological techniques (Eigenberg et al., 2002) have also been employed to monitor the pathway of solute movement in the soil.

Computer models have also been developed for scientific research based on ecosystem management principles

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(Ma et al., 2001). The soil N balance estimation system was developed as a decision support tool for rational fertilizer management in upland farms (Sugahara et al., 2003) in Japan. A performance test of the system was carried out using lysimeter experimental data to clarify the capability of this empirical model to estimate $\text{NO}_3\text{-N}$ leaching in the North and Central part of Japan (Chotangui et al., 2013). However, the applicability of this model to estimate $\text{NO}_3\text{-N}$ leaching in current intensive-profit-oriented fields of leafy vegetables characterized by an array of nutrient management options is lacking.

Previous studies have shown that there is a strong positive relationship between bulk electrical conductivity of the soil (EC_b) and soil solution electrical conductivity (EC_w) (Krishnapillai and Ranjan, 2009); EC_w and ionic concentration (C_i) (Wraith and Das, 1998; Scudiero et al., 2012). In addition, a strong positive correlation between soil $\text{NO}_3\text{-N}$ concentration and EC_b has been reported (Patriquin et al., 1993; Stamatiadis, 1999; Eigenberg et al., 2002; Hu et al., 2005; Payero et al., 2006; Ju et al., 2007). In this study, we hypothesized that the multifunction capacitance/resistance sensor ($\text{ECH}_2\text{O-5TE}$, 70 MHz, Decagon Devices, Pullman, WA, USA, hereafter mentioned as 5TE) that uses the same principle as the time domain reflectometry can be applied to continuously monitor the soil $\text{NO}_3\text{-N}$. Soil $\text{NO}_3\text{-N}$ was monitored to provide real-time data that was used to verify the leaching constant and temperature sub models integrated in the soil N balance estimation system that was subsequently used to evaluate $\text{NO}_3\text{-N}$ leaching.

The main aim of this study was to evaluate $\text{NO}_3\text{-N}$ in commercial fields of intensive leafy vegetable production systems using the soil N balance estimation system. The specific objectives included: (i) to verify the $\text{NO}_3\text{-N}$ leaching constant and soil temperature sub-model integrated in the soil N balance estimation system, (ii) to monitor soil $\text{NO}_3\text{-N}$ fluxes and plant N uptake in commercial fields under different nutrient management options and (iii) to evaluate $\text{NO}_3\text{-N}$ leaching below the rooting zone.

MATERIALS AND METHODS

Study site

The study was carried out at the Nobeyama plateau located at the foot of the Yotsugatake mountains ($35^\circ 57' \text{N}$, $138^\circ 28' \text{E}$), Nagano prefecture, Central Japan. On these highlands, farmer's fields for summer vegetable production have been established on the lower volcanic slopes of the highlands at 1220–1350 m (above sea level, asl.) (Table 1). The region has a typical monsoon climate similar to that of Mito (Chotangui et al., 2013), with an average annual temperature of 6.9°C (maximum and minimum temperature of 12.3°C and 1.5°C , respectively) and mean annual precipitation of about 1464 mm (Nobeyama Meteorological Data System, Japan Meteorological Agency). The region is a famous production area of leafy vegetables and dairy produce (fresh milk, calves) in Japan.

The soil type in this region is derived from volcanic ash and classified as cummulic Allophanic Kuroboku soil (Table 1: united soil classification of Japan) which are dead

Table 1 Location and the basic characteristics of the topsoil (0–20 cm) of the selected fields.

Location				Physical properties					Chemical properties								
Field	Latitude ($^{\circ}$)	Longitude ($^{\circ}$)	Altitude (m) asl.	Bulk density (g g $^{-3}$)	Soil moisture content (g g $^{-1}$)	Sand (%)	Silt (%)	Clay (%)	Soil texture	Soil colour	pH $_{1.5}$	TDS (mg ml $^{-1}$)	EC $_{1.5}$ (μ S cm $^{-1}$)	Total C (%)	Total N (%)	NO $_3$ -N (mg kg $^{-1}$)	NH $_4$ -N (mg kg $^{-1}$)
A $_1$	36.8	139.1	1373.4	0.60	0.83	63.6	22.8	13.6	Sandy-Loam	Black-brown	6.40	50.0	0.120	10.54	0.74	9.93	0.52
A $_2$	36.9	139.2	1367.0	0.63	0.71	58.1	20.9	21.0	Sandy-clay-loam	Black-brown	6.40	40.0	0.100	5.61	0.41	3.78	0.47
A $_3$	36.0	138.6	1364.6	0.81	0.65	60.4	21.8	17.8	Sandy-Loam	Black	6.30	80.0	0.160	6.37	0.45	6.16	0.42
B $_1$	36.3	138.6	1370.4	0.70	0.68	55.6	24.1	20.3	Sandy-clay-loam	Black-brown	6.30	60.0	0.140	7.24	0.53	10.91	0.37
B $_2$	36.0	139.2	1333.2	0.92	0.62	54.4	22.0	23.6	Sandy-clay-loam	Black-brown	6.40	80.0	0.180	5.46	0.41	10.96	0.39
B $_3$	36.2	139.3	1264.0	0.81	0.66	54.4	20.0	25.6	Sandy-clay-loam	Brown	6.45	100.0	0.210	5.16	0.41	40.43	0.36
C $_1$	36.8	139.1	1248.2	0.79	0.62	50.2	35.2	14.6	Loam	Black-brown	6.40	50.0	0.120	4.72	0.37	20.51	0.31
C $_2$	36.8	139.1	1243.3	0.83	0.52	44.0	31.6	24.3	Loam	Brown	6.80	50.0	0.110	2.01	0.19	13.98	0.36
C $_3$	36.9	138.7	1251.2	0.71	0.61	44.8	39.1	16.1	Loam	Black-brown	6.70	80.0	0.170	3.76	0.3	8.53	0.26
AFC $_1$	36.8	139.0	1350.0	0.67	0.61	58.9	30.9	10.2	Sandy-Loam	Black	6.90	30.0	0.080	8.79	0.59	5.31	0.32
AFC $_2$	36.8	138.9	1350.0	0.72	0.68	60.3	26.0	13.8	Sandy-Loam	Black	6.60	30.0	0.080	7.85	0.54	2.82	0.37
AFC $_3$	36.6	138.5	1357.9	0.69	0.71	66.8	16.0	17.2	Sandy Loam	Black	6.30	40.0	0.090	9.55	0.64	5.39	0.58

asl: above sea level.

Table 2 Characteristics of the soil NO₃-N monitored fields, representing each farm.

Monitored Field	Monitoring Period	Cropping system	Plowing	Stubble cultivation	Type of fertilizer
AFC₁	Apr 13th 2012–Apr 8th 2013	Single: Cabbage	Every 4 Years	No	Controlled-release
C₃	Apr 13th 2012–Apr 8th 2013	Single: Lettuce	Every Year	No	Conventional
A₃	Apr 4th 2013–Sept 18th 2013	Double: Lettuce-Cabbage	No	At 50 cm	Conventional
B₃	Apr 4th 2013–Sept 18th 2013	Double: Lettuce-Cabbage	No	At 35 cm	Conventional

volcanoes and andesitic lavas derived from Pleistocene and Holocene (Matsuyama and Saigusa, 1994; Shinjo et al., 2006).

Farm and nutrient management practices

Vegetable production in this area comprises mainly crisp-head type lettuce (*Lactuca sativa* L.), Chinese cabbage (*Brassica rapa* L. ssp *pekinensis*), cabbage (*Brassica oleracea* L.). Crop rotation patterns involved leafy vegetables, leguminous crops (flower bean), green manure species (new Oats and rye) and gramineous crops (timothy, sorghum and sweet corn). Double cropping within a season is a common practice in commercial fields characterized by early planting in spring. Planting material comprises both ordinary and resistant varieties in association with disease and pest management practices that varied with the farmer's perception. Plastic mulching is also a common practice.

Generally, organic manure made of cow dung mixed with bedding material, rice husks, plant debris and sawdust of varying proportions depending on the farm management was applied in fall, incorporated by stubble cultivation and allowed to overwinter. Chemical fertilizer application varied in type and quantity. The mode of application was mainly through basal application followed by rotary tillage to the depth of 0.20 m. Incorporation of plant residues into the soil after harvest was also a common practice. Subsurface drainage was achieved by the use of buried pipe systems in the subsoil layer and stubble cultivation to the depth of about 0.50 m.

Methodology

Twelve fields belonging to four different farmers were selected in the Nobeyama and Kawakami areas of the Nagano Prefecture. Three of the farmers were commercial growers recommended by the agricultural extension service of the Saku center of the Nagano Prefecture. The other fields were experimental fields of education and research centre of Alpine Field Science (AFC) owned and managed by Shinshu University. For each farmer, three fields were randomly selected as sampled representatives of the prevailing cropping systems in the area. The farms/farmers were denoted by a capital letter(s) (A, B, C and AFC) and the sampled fields by a number (Table 1).

In farms A and AFC the so-called “intelligent fertilizers” (controlled-release fertilizers) was while in farms B and C conventional N fertilizers was applied. Land preparation was similar in all the four farms except for the fact that farms A and B carried out stubble cultivation to the depth of 0.50 m and 0.35 m, respectively. Farms AFC and C were plowed once in every four years and yearly, respectively.

Field monitoring of soil NO₃-N using the 5TE was

conducted in four fields for two years (AFC₁ and C₃ in 2012; A₃ and B₃ in 2013). The study was designed such that monitored fields comprised single cropping systems in 2012 (Table 2) and double cropping systems in 2013 (Table 2). Two 5TE sensors (within and below the rooting zone) were implanted in the fields in 2012. In 2013, the 5TE sensors were implanted in duplicates per soil layer making a total of four per field and adjacent to the sensors were two soil water samplers to collect sub soil solution. In fields where rye was planted in fall after harvest, NO₃-N leaching was evaluated with and without the consideration of N uptake (aboveground biomass) in fall as N input in the following cropping season.

Configuration and testing of the capacitance-resistance sensor (5TE)

The 5TE sensor was designed and calibrated purposely to measure the soil dielectric permittivity (ϵ), bulk electrical conductivity (EC_b) and the soil temperature. Detailed description of the 5TE sensor is found in Scudiero et al. (2012) and Decagon Devices Inc., Pullman, WA, USA. Prior to field installation and monitoring, the 5TE sensors were connected to a 50Em data logger. The 50Em data logger was connected to a computer with appropriate software and configured to scan data from the 5TE sensors at ten min time interval based on the time interval of the automated meteorological data acquisition system (AMeDAS) in Japan. Appropriate measurement units for all parameters (soil moisture content, temperature and EC_b) were also specified in the logging software.

Sensitivity of the 5TE sensors to detect changes in NO₃-N concentration as changes in EC_b was verified in the laboratory using a 1000 mg L⁻¹ solution of potassium nitrate and appropriate dilution with de-ionized water at various time intervals to alter the NO₃-N concentration of the solution. The 5TE pods on the data loggers were interchanged and the procedure repeated. EC_b readings of the 5TE sensors and NO₃⁻-N concentration of the solution were recorded.

Field monitoring of soil NO₃-N

On-farm measurements and modeling was employed in this study to estimate soil NO₃-N concentrations in drainage, NO₃-N leaching and drainage volume. Field monitoring of soil NO₃-N was conducted over two years in four different fields (Table 2). The 5TE sensors were used based on the linear relationship between soil NO₃-N and EC_b . The 5TE sensors were implanted into the soil following fertilizer application and plastic mulching at the depths of 10–13.2 cm (top soil layer) and 40–43.2 cm (subsoil layer) corresponding to the rooting and below the rooting zone, respectively. These depths were based upon the rooting depth of the cultivated vegetables (20–25 cm), the

Table 3 Aboveground biomass, N and moisture content of cultivated crops in 2012

Cultivated crop	Field ^a	Fresh weight (g/plant ⁻¹)		Dry weight (g/plant ⁻¹)		N (%)		Moisture content (%)	
		Harvested	Residue	Harvested	Residue	Harvested	Residue	Harvested	Residue
L (sunny)	A ₁	357.70c	398.47bcd	15.99de	19.22d	2.37de	2.76de	95.53abcd	95.16ab
	A ₂	343.23c	357.90bcd	16.86de	21.51cd	2.39de	2.76de	95.05bcde	94.04abc
	B ₁	533.70c	447.89bcd	16.09de	18.46d	2.78cd*	4.05bc	96.93ab	95.84abc
	B ₂	345.90c	271.03cd	14.48de	15.79cd	1.65e	2.31ef	95.72abc	94.21abc
	B ₃	509.75c	337.49bcd	30.64cd	21.90d	3.24c	3.77c	93.97cde	93.50bcd
	B ₃ ^z	613.75c	351.14bcd	21.11de	12.45d	4.05b	3.28cd	96.59ab	96.43a
	C ₁	420.86c	261.42d	17.02de	14.04d	2.83cd	3.41cd	95.95ab	94.61abc
	C ₁ ^z	302.30c	292.54bcd	9.50e	10.78d	4.10b	4.71ab	96.84ab	96.23ab
	C ₃	379.65c	227.03d	12.07de	12.21d	3.27c*	3.93c	96.84ab	94.63abc
Mean		422.98	327.21	17.08	16.26	2.96	3.44	95.94	94.90
C	AFC ₁	1326.77b*	629.74bc	84.12b*	57.46ab	1.93e	1.84f	93.61e*	90.82de
C	AFC ₃ ^y	538.69c	643.71b	45.04c*	69.28a	4.05b	3.90c	91.56f	89.23e
C	B ₃ ^z	2077.38a*	547.54bcd	129.37a*	42.37bc	2.71cd	3.30cd	93.65de	92.04cde
Mean		1314.28	606.99	86.18	56.37	2.90	3.01	92.94	90.70
CC	A ₃	2442.24a*	1730.89a	73.01b	72.78a	5.01a	5.27a	96.99a	95.56ab

L: Lettuce, C: Cabbage, CC: Chinese cabbage.

^a: Second crop in the same field.^z: Clubroot disease experimental field.Means within a column, followed by a common lowercase letter are not significantly different ($P > 0.05$, Tukey HSD).*Means for harvested and residue are significantly different ($P < 0.05$, Tukey HSD).**Table 4** Aboveground biomass, N and moisture content of cultivated crops in 2013

Cultivated crop	Field	Fresh weight (g/plant ⁻¹)		Dry weight (g/plant ⁻¹)		N (%)		Moisture content	
		Harvested	Residue	Harvested	Residue	Harvested	Residue	Harvested	Residue
L	A ₃	521.34d	308.42de	17.27d	12.66c	4.4a	4.65a	96.71a	95.86a
L	B ₁	417.88d	288.27de	15.10d	13.65c	4.0ab	4.65a	96.35ab	95.22ab
L	B ₂	580.57cd	325.22de	23.65cd	17.26c	3.38bc*	4.36ab	95.92abcd	94.64ab
L	B ₃	723.90cd	379.64de	19.35cd	14.81c	4.3a	4.98a	97.28a	96.08a
L	C ₁	521.70d	202.74e	20.77d	13.48c	3.24b	3.64bc	96.02abc	93.33bc
L	C ₃	475.94d	182.11e	27.15d	15.81c	2.70cde	3.45c	94.29bcd	91.30de
Mean		540.22	281.07	20.55	14.61	3.68	4.29	96.09	94.40
C	C ₂	1326.83bc*	501.81cde	84.77ab	49.59ab	2.18e	2.64de	93.62d	90.10ef
C	AFC ₂	1444.55b	867.46bc	88.74ab	66.78ab	2.48de*	3.52c	93.87cd	92.32cd
C	AFC ₃ ^y	752.16cd	527.78cde	66.40bc	58.13ab	2.97cd	2.50e	90.40e	88.54f
C	A ₃ ^z	1354.13bc*	655.66cd	77.59ab	54.02ab	2.74cde	3.3cd	94.35bcd	91.77cde
C	B ₃ ^z	1422.99b	884.96bc	79.99ab	71.23ab	2.98cd*	3.83bc	94.31bcd	91.94cde
Mean		1695.19	886.00	87.06	61.80	2.67	3.16	94.13	92.15
CC	A ₁	2492.72a*	1252.97ab	92.05ab	56.32ab	4.42a	4.62a	96.25ab	95.47a
CC	A ₂	3073.00a*	1511.33a	119.91a*	76.51a	4.33a	4.99a	96.11abc	94.94ab
Mean		2782.86	1382.15	105.98	66.41	4.37	4.81	96.18	95.20

L: Lettuce, C: Cabbage, CC: Chinese cabbage.

^a: Second crop in a double cropping sequence.^y: Experimental field for club-root disease.

depth of rotary tillage (20 cm), the soil profile and the soil management practice.

Sensors were implanted by horizontal insertion of the prongs through the vertical face of a small trench (approximately $40 \times 20 \times 55 \text{ cm}^3$) that was dug on the furrow between two ridges (Payero et al., 2006). Inserted sensors were then connected to a 50Em data logger powered by a 12-V battery. The connected 5TE sensors were allowed to stabilize and scan the first three data sets before back-filling of the trench. The trench was back-filled and packed properly to re-construct the initial characteristics of the soil with special attention to soil bulk density and horizon. Data were manually downloaded from the data loggers at 2–3 weeks' time interval throughout the monitoring period (Table 2).

Soil and plant; sampling and analysis

Non-destructive monitoring of soil $\text{NO}_3\text{-N}$ by the 5TE

sensors was accompanied by periodic sampling of the soil and cultivated crops. Aboveground plant parts in triplicates and soil at 5–7 different positions within the field were sampled, placed in a portable cooler and taken to the laboratory for analysis periodically. Plant fresh and dry weight after drying in an air-circulating oven at 80°C was determined. Dried plant materials were ground in an electric mill (MILLSER-720-G-W, Iwatani Japan), sieved through a 2 mm mesh and the N content analyzed using a C/N analyzer (CN CORDER MT-700, Shimadzu, Japan).

For each field, the soil subsamples were bulk together to form a composite sample. Sampling spots were back-filled to minimize or mitigate downward preferential flow after rainfall events. Samples were taken to the laboratory and kept in a freezer at 4°C for analysis the next day. Soil texture for the top soil samples was determined for samples collected before manure application in November 2011 at

the beginning of the study (Table 1). Standard laboratory analyses were carried out to obtain the physical and chemical properties of soil samples. Soil NO₃-N and NH₄-N were analyzed by colorimetric methods of UV-VIS spectrophotometer (Shimadzu, Japan).

Sub soil solution

Coupled to soil NO₃-N monitoring by the 5TE sensors, soil water samplers (DIK-8392) measuring 50 cm in length with an in-built collecting tube, a porous cup, a syringe having a 3-direction cock and a stopper were installed in duplicates at the same sub soil depths as the 5TE sensors in fields monitored in 2013 (A₃ and B₃). Soil solution samples were sampled by applying a suction pressure in a vinyl hose connecting to the sampler. Soil solutions were sampled during the day and night of the same sampling date as the soil and plants.

The soil water samplers were gradually inserted into a vertical hole that was created by screwing a soil auger through the soil to a depth of 45 cm such that the porous cup was at the same depth as the 5TE sensors in the sub soil layer. NO₃-N of the soil solution was used to verify the reliability of the 5TE readings at the level of the field. Laboratory experiments were also conducted using air-dried soil samples collected from the monitored fields to check on the reliability of the 5TE sensor readings of soil moisture content and temperature (data not shown).

Verification of the leaching constant and the soil temperature sub-model of the soil nitrogen balance estimation system

The leaching constant integrated in the soil nitrogen balance estimation system (0.0007 kg kg⁻¹) was verified using the sub soil NO₃-N concentrations and soil moisture contents obtained by the 5TE readings. Soil EC_b obtained by the 5TE sensors were transformed into soil NO₃-N using the linear equations between the soil NO₃-N concentration and EC_b readings of the 5TE. The ten min interval readings were converted to daily readings using pivot tables and appropriate functions in Microsoft Excel. A scattered plot between sub soil moisture content (mm m⁻³) and sub soil NO₃-N (mg m⁻³) soil below the rooting zone was used to verify the leaching constant. The data sets were fitted using linear regression and the equations were used to calculate sub soil NO₃-N (mg m⁻³) concentration at 1000 mm m⁻³.

Top soil temperature estimated in the soil N balance estimation system was correlated with the 5TE microthermistor measurements to verify top soil temperature estimated by the soil N balance estimation system.

NO₃-N leaching by the soil nitrogen balance estimation system

Estimates of soil NO₃-N leaching in the selected fields were evaluated by the soil nitrogen balance estimation system for the cropping seasons of 2012 and 2013. N mineralization parameters (NMP) of cummulic (farm A, AFC, and B) and low-humic (farm C) Andosols were used as input data of the soil N mineralization sub model in the system. Input values of N content and aboveground biomass obtained at harvest, N fertilizer applied, soil chemical properties, organic manure applied, NMP of cow

Table 5 Soil NO₃-N leaching and N balance in 2012

Evaluation: 13th April-Harvesting date			Inorganic N kg ha ⁻¹						Accumulated water (mm)		
Field	Crop	Harvesting date	Fertilizer applied	Manure mineralized N	Soil mineralized N	Soil initial N	N uptake (aboveground)	Leached NO ₃ -N	Soil residual N	Percolate water	Rainfall
A ₁	L	8-Aug-12	90.0	25.36	24.35	64.02	78.92	32.75	92.05	375	598
A ₂	L	8-Aug-12	90.0	25.36	20.89	14.01	87.07	16.85	37.36	375	598
A ₃	CC	26-Sep-12	340.0	32.71	46.60	20.44	327.15	37.86	74.74	480	766
B ₁	L	3-Sep-12	264.0	20.19	27.51	21.11	104.80	67.15	160.86	421	671
B ₂	L	3-Sep-12	234.0	20.19	36.15	11.13	54.57	72.71	174.19	421	671
B ₃ ^z	L-L	24-Aug-12	356.0	19.14	35.66	19.47	269.53	42.69	118.05	379	653
B ₃ ^z	L-C	25-Sep-12	201.6	21.80	46.48	19.47	165.33	28.24	62.42	445	766
CI ^z	L-L	25-Sep-12	87.0	9.25	30.88	9.26	378.79	26.69	58.98	445	766
C ₃	L	3-Sep-12	194.1	8.52	23.63	6.93	76.37	42.79	114.02	390	671
AFC ₁	C	8-Aug-12	150.0	51.55	18.64	6.78	175.53	13.50	37.94	375	598
AFC ₃	C	3-Sep-12	171.0	57.09	27.11	21.00	136.01	41.29	98.91	421	671

L: Lettuce, C: Cabbage, CC: Chinese cabbage. ^z: Second crop in the same field.

Table 6 Soil NO₃-N leaching and N balance in 2013

Field	Crop	Harvesting date 2013	Inorganic N kg ha ⁻¹					Accumulated water (mm)		
			Fertilizer applied	Manure mineralized N	Soil mineralized N	N mineralized: Rye	Soil initial N	N uptake (aboveground)	Leached NO ₃ -N	Soil residual N
A ₁ without Rye	CC	4-Jul-13	228.0	12.37	10.14	—	11.59	303.38	0.00	-41.28
	CC	4-Jul-13	228.0	12.37	10.14	129.32	11.59	303.38	8.66	79.38
	CC	15-Aug-13	300.0	20.77	27.21	—	11.44	396.09	0.00	-36.67
	CC	15-Aug-13	300.0	20.77	27.21	106.20	11.44	396.09	9.06	60.53
	L-C	17-Sep-13	230.0	25.44	48.17	—	8.89	216.88	21.98	73.63
B ₁	L	3-Sep-13	306.0	16.33	30.35	—	8.80	97.39	41.10	223.00
	L	14-Aug-13	220.0	13.74	31.30	—	6.88	136.37	17.64	117.91
	L-C	18-Sep-13	492.0	17.43	48.31	—	6.94	444.45	29.53	90.71
C ₁	L	4-Jul-13	201.6	0.00	9.32	—	8.80	91.39	13.52	115.19
	C	4-Sep-13	240.0	0.00	30.53	—	26.59	277.26	3.36	16.49
	L	14-Aug-13	194.1	0.00	20.34	—	11.58	112.24	15.82	97.97
AFC ₂	C	31-Jul-13	150.0	25.97	19.28	—	8.51	250.15	0.00	-46.39
AFC ₃	C	4-Sep-13	180.0	26.58	30.14	—	7.78	188.49	9.49	46.52

L: Lettuce, C: Cabbage, CC: Chinese cabbage. ^z: Second crop in the same field.

manure and the climatic data of AMeDAS point 48571 at 1350 m (Nobeyama) were used. Soil samples collected on 13th April 2012 and 8th April 2013 were used as input data for the evaluation of NO₃-N leaching in the system.

Percolating soil water was estimated by applying the water balance approach (Asadi and Clemente, 2003; Parent and Anctil, 2012) as follows; $DPR = I + P + C_r - \Delta S - ET - R$ where DPR is percolating soil water (mm), I is irrigation water (mm), P is precipitation (mm), C_r is capillary rise, ΔS is change in soil water storage (mm), ET is evapotranspiration (mm), and R is run-off (mm). Surface run-off, capillary rise and irrigation were considered to be negligible in this study. Actual evapotranspiration for the Nobeyama area was estimated from the FAO reference evapotranspiration (ET_o) using the FAO-56 dual crop coefficient procedure (Allen et al., 1998; Allen, 2000). Basal crop coefficient values at the initial and mid-season stages ($K_{cb\ ini}$ and $K_{cb\ mid}$) of growth and development for non-stressed crops under sub-humid climates were used. The crop coefficient values were adjusted to the climatic data and characteristics of the cultivated crops according to FAO-56 procedure to obtain daily values. Water stress coefficient was not taken into consideration. The minimum crop coefficient (K_c) was set to 0.10 rather than the recom-

Fig. 1 Laboratory test showing the relationship between the solution NO₃-N content and bulk electrical conductivity of the 5TE sensor using 1000 mg L⁻¹ NO₃-N solution. **Fig. 2** The relationship between the soil NO₃-N and the bulk electrical conductivity of the 5TE at the level of the field in 2012 (a) and 2013 (b) cropping seasons.

mended 0.15 due plastic mulching of the fields.

Fields above 1300 m asl. (Table 1) were grouped together and evaluated using the percolating soil water value of the field where the 5TE was implanted and below 1300 m were grouped together. Thus for each cropping season, one field above and one below 1300 m was monitored. NO₃-N leaching for each field was evaluated from the same date when soil samples were collected for all the fields (13th April for 2012 and 8th April for 2013) to the harvesting date (Tables 5 and 6). NO₃-N leaching was not evaluated for fields where flower beans was cultivated (AFC₂ and C₂ in 2012; AFC₁ in 2013).

Data analysis

Spreadsheets were prepared in excel 2007 and imported into SPSS 18.0 for statistical analysis. Simple linear regression, student t-test and analysis of variance (ANOVA) with means separated using Tukey HSD at $P=0.05$ significance level were used.

RESULTS AND DISCUSSION

Laboratory test of the 5TE sensor and soil NO₃-N-EC_b relationship

Results of the laboratory test using the NO₃-N solution showed a strong significant correlation ($P<0.05$ and $R^2=0.98$) between NO₃-N concentration of the solution and EC_w detected by the 5TE sensor (Fig. 1). This confirms findings reported by Krishnapillai and Ranjan (2009). The strong positive correlation was due to the homogenous nature of the solution and deviations or outliers were expected in heterogeneous media such as soils of intensive vegetable production. The reliability of using the soil EC_b as an index of soil NO₃-N was observed on soil EC_b and NO₃-N of soil

samples collected before planting and at harvest in 2012 and 2013 (data not shown). Also, soil NO₃-N sampled throughout the cropping seasons of 2012 and 2013 showed a strong positive correlation with EC_b readings of the 5TE sensors (Fig. 2). This portrays similar results reported by Patriquin et al. (1993), Stamatiadis, (1999), Eigenberg et al. (2002), Hu et al. (2005), Payero et al. (2006) and Ju et al. (2007). Correlation between soil NO₃-N and soil EC_b was generally similar amongst the fields evaluated in the same year (Fig. 2). This indicates the effects of farm management, climatic conditions and other soil variables on the sensitivity and or functioning of the 5TE sensors. The relatively weak relationship between soil NO₃-N and EC_b of the 5TE sensors (Fig. 2) compared to that between the NO₃-N solution and EC_b of the 5TE sensors (Fig. 1) was due to interference of the soil texture and other soil variables on 5TE sensors functioning. The strong correlation between the sub soil solution NO₃-N and EC_b of the 5TE sensors collected in 2013 also confirmed the reliability of EC_b of the 5TE sensors as an index of soil NO₃-N (Fig. 3).

The scatter plots for the top and sub soil layers were similar for fields monitored in the same cropping season (Fig. 2a, b). This exposes the effect of the climate (rainfall) on the movement of soil NO₃-N within and below the rooting zone in fields of similar farm and crop management practices (Table 2). In addition, NO₃-N of the sub soil solution obtained from the porous ceramic cups of the soil water samplers strongly correlated to sub soil NO₃-N obtained from the 5TE EC_b readings. However, the data points were below the line $y=x$ indicating the 5TE overestimated soil EC_b (Fig. 4). Overestimation may have been caused by interference of other soil properties with prongs of the 5TE sensors.

Temporal variability of the soil moisture, temperature and soil NO₃-N with climate and N uptake

Rainfall and crop N uptake affected soil NO₃-N and moisture fluxes in the rain-fed commercial fields of vegetable production monitored. Transformed EC_b readings of the 5TE throughout the monitored period generally showed soil NO₃-N fluxes within and below the rooting zone (Fig. 5a, b). Dual measurements of the soil NO₃-N and the soil moisture content in the laboratory showed that below a certain level of soil moisture content, the 5TE sensor is unable to detect changes in soil moisture and bulk EC_b (data not shown).

Sub soil moisture content in all the monitored fields was dependent upon the top soil moisture content which was dependent upon rainfall throughout the cropping season (Fig. 5a; 13th April 2012 to harvest 2012, 5b; 8th April 2013 to 18th September 2013). Sharp peaks indicating increments of the soil moisture content occurred during short intense or long less-intense rainfall events especially when the initial soil moisture content was very low (Fig. 5a, b). Changes in soil moisture content in the top soil affected the sub soil moisture content and consequently the sub soil NO₃-N in some rainfall events (Fig. 5a: from 13th April in 2012, 5b: from 8th April to 17th September in 2013 and soil solution NO₃-N in 2013). Such increments indicated that the soil percolating water as a result of a rainfall is the

Fig. 3 Relationship between NO₃-N of the sub soil solution and bulk electrical conductivity of the 5TE at the level of the field in 2013. * indicates level of significance ($P<0.05$).

Fig. 4 Correlation between NO₃-N estimated from the 5TE sensor EC readings and NO₃-N of the soil solution of water samplers in 2013.

1: Fertilizer application and plastic mulching, 2: Sensor implantation, 3: Transplanting -1st crop, 4: Harvesting -1st crop, 5: Transplanting -2nd crop, 6: Harvesting -2nd crop, vertical bars indicate daily rainfall.

Fig. 5 Temporal variability of soil temperature, soil moisture and soil NO₃-N throughout the cropping seasons of 2012 (a) and 2013 (b).

Fig. 6 Temporal biomass accumulation and N uptake throughout the cropping seasons of 2012 (a and b) and 2013 (c). Data not available for A₃.

transport medium of NO₃-N leached below the rooting zone. However, only rainfall events greater than 5 mm and of longer duration resulted to observable leaching of NO₃-N below the rooting zone as indicated by a rise on the sub soil NO₃-N curve (Fig. 5a, b).

Top soil NO₃-N was highest during the initial stage of growth (approximately 6 mg 100 g⁻¹ for AFC₁ and 4 mg 100 g⁻¹ for C₃ in 2012; 14 mg 100 g⁻¹ for A₃ and 24 mg 100 g⁻¹ for B₃ in 2013) as shown in Fig. 5a, b. This resulted to high leaching rates during the initial stages of growth and development and low leaching rates during the developmental stages of growth. In field C₃, top soil NO₃-N was relatively low due to the long time interval (almost a month) between fertilizer application and transplanting of seedlings. During this time laps characterized by no crop N uptake, the applied N fertilizer was liable to leaching following rainfall resulting a to soil water content above the field capacity and consequently leaching of soil NO₃-N into the sub soil (Fig. 5a). This shows that available soil NO₃-N in synchrony with crop N uptake minimizes NO₃-N leaching and improves N use efficiency in vegetable production systems. Also, the application of controlled-release fertilizers played an important role in limiting NO₃-N leaching as was the case in AFC₃ in 2012 (Fig. 2a). This confirms the use of slow-release or controlled release fertilizers to reduce ground water contamination through NO₃-N leaching (Kumazawa, 1999; Mishima, 2001; Maeda et al., 2003; Bergström, 2005; Ju et al., 2007).

NO₃-N leaching indicated by increments of the sub

soil NO₃-N was highest during the initial stage of growth and development for all the monitored fields (Fig. 5a, b). NO₃-N leaching was higher in 2012 compared to the 2013 cropping season as indicated by the smaller gap between the top and sub soil NO₃-N content (Fig. 5a, b). Also, leaching after harvest in 2012 was observed resulting from rapid decomposition of plant residues of low CN ratio of the single vegetable cropping systems (Fig. 5a, b). A flush of sub soil NO₃-N was observed in April 2013 in AFC₁ and C₃ occurred as a result of leaching by a high drainage volume following the melting of winter snow (Fig. 5a). Low NO₃-N leaching below the rooting zone was observed during the crop developmental stage of growth when N uptake was highest (Figs. 5 and 6).

Generally, crop N content of Chinese cabbage was higher than that of lettuce which was higher than that of lettuce except for the field AFC₃ (2012) in which N content of cabbage was similar to that of lettuce (Tables 3 and 4). This was as a result of the clubroot disease in AFC₃ that greatly damaged the roots, thus affecting N uptake. Crop N content between the three leafy vegetables for each cropping season (2012 and 2013) showed a significant difference ($P < 0.05$) (Tables 3 and 4). But interestingly, the N content of the same crop showed no significant difference ($P > 0.05$) between the fields indicating that N fertilizer applications above a certain level had no significant effect on yield (Tables 3 and 4).

Soil temperature and the leaching constant

Temperature of the top soil layer was higher than that of the sub soil layer throughout the cropping season but the reverse was true during winter (Fig. 5a). Soil temperature at both depths gradually increased from the beginning to the end of the cropping season with the highest values recorded in the month of July (summer). This shows that the atmospheric temperature affected the top soil temperature through heating. Consequently, top soil temperature estimated by the model showed a strong positive correlation with the temperature readings of the 5Te sensor throughout the cropping season (Fig. 7). This validates the daily standard temperature (DTS) estimated in the N mineralization sub-model incorporated in the soil N balance estimation system. However, outliers on Fig. 7 indicated values recorded during the winter period. This indicates that the soil mineralization sub-model integrated within the soil N balance estimation systems is reliable during the cropping season. Thus, in this study, NO₃-N leaching by the soil N balance estimation system was evaluated for the period between transplanting and harvesting (cropping season).

Linear relationship between the sub soil moisture and sub soil NO₃-N of the 5TE sensors showed that at sub soil moisture content of 1000 mm m⁻³ (as 1000 mm m⁻¹), sub soil NO₃-N which was equal to the leaching constant was -0.0010 kg m⁻³ (for AFC₁) and 0.00127 kg m⁻³ (for C₃) in 2012, 0.00060 kg m⁻³ (for B₃) and 0.00075 kg m⁻³ (for A₃) in 2013 (Fig. 8a, b). This gives an overall average of 0.00087 kg m⁻³ (considering the positive values) which is closer to the model value of 0.0007. The negative value for AFC₁ was as a result of the controlled release fertilizer applied to the field and the compact nature of the soil below

Fig. 7 Correlation between measured and estimated top soil temperature.

Fig. 8 Relationship between sub soil percolating water and NO₃-N leaching in (a) 2012 and (b) 2013.

the depths of 0.25 m. The higher value of 0.00127 for C₃ may have been caused by the long time interval between fertilizer application and transplanting during which high amounts of the applied fertilizer was leached into the sub soil layer. Also, lack of replicates of the 5TE sensors for each soil layer may have contributed to the results in 2012. Fields monitored in 2013 had values closer to the leaching constant in the soil N balance estimation system. These fields were monitored throughout the cropping season with the 5TE sensors implanted at each soil layer in duplicates. Farm management practices of the two fields in 2013 were similar without any compaction observed in the sub soil layer and no time interval between fertilizer applications and transplanting.

Soil percolating water and NO₃-N leaching

Soil percolating water estimated as a percentage of accumulated rainfall using the water balance approach was 62.70% (AFC₁) and 58.10% (C₃) in 2012, 50.53% (A₃) and 53.97% (B₃) in 2013. These values are closer to 54.9% estimate of water infiltrating into the soil in Japan after evapo-transpiration (Mishima, 2001). These input values were used to run the soil N balance estimation system with AFC₁ and A₃ representing fields above 1300 m (asl), C₃ and B₃ representing fields below 1300 m (asl) (Table 1).

NO₃-N leaching was highest for fields of farm B in 2012 (72.71 kg ha⁻¹) and 2013 (42.10 kg ha⁻¹) probably due to high N fertilizer application (Tables 5 and 6) with no significant difference in yield and crop N content (Tables 3 and 4) for the same crops under different management

Fig. 9 Correlation between model estimates of NO₃-N leached and the sub soil NO₃-N content at harvest in 2012 and 2013. * indicates level of significance ($P < 0.05$).

practices (farm A, B, AFC and C). This is in conformity with previous studies that N fertilizer application in excess results to high risk of NO₃-N leaching and subsequent contamination of ground water (Kumazawa, 1999; Maeda et al., 2003; Bergström, 2005; Ju et al., 2007). NO₃-N leaching ranged from 13.50 kg ha⁻¹ to 72.71 kg ha⁻¹ in 2012 and 8.66 kg ha⁻¹ to 41.10 kg ha⁻¹ or 0.00 kg ha⁻¹ to 41.10 with or without rye respectively, in 2013 (Tables 5 and 6). For both years, the lowest leaching rates were observed in farm AFC and C. Leaching in double cropping systems were lower than in single cropping systems (Tables 5 and 6). Rye cultivated in fall 2012 in A₁ and A₂ served as a catch crop of N. Leaching of NO₃-N in these fields without the consideration N uptake by rye in fall and subsequent release (decomposition) in the following cropping season was 0.00 but when taken into consideration, the model estimated leaching to be 8.6 and 9.1 kg ha⁻¹ for A₁ and A₂, respectively. This equally shows that organic manure N not mineralized during the cropping season contributed to soil N status in the next cropping season. That is, rye or oats cultivated in fall as green manure served as a catch crop that conserved N over winter and was released through mineralization in the next cropping season. NO₃-N leaching was higher in 2012 than in 2013 and this may have been probably due to the fact that 2012 was relatively a wetter year confirming findings of Gheyari et al. (2009).

A strong positive correlation between the sub soil NO₃-N at harvest and leached NO₃-N estimated by the soil N balance estimation system indicated that the model estimates were reliable (Fig. 9). Estimated NO₃-N leached in double cropping systems (2013) was lower than in single cropping systems (2012). The use of controlled-released fertilizers also played a role in reducing NO₃-N leaching as was observed in AFC₁ in 2012 (Table 5).

Conclusion

Our study combines on-farm measurements and modeling to evaluate NO₃-N leaching in commercial fields of vegetable production characterized by single and double cropping. The results showed that the non-destructive monitoring technique using the 5TE sensors can be applied to revealed high risk of NO₃-N leaching throughout the cropping season. Observed trends of soil NO₃-N with rainfall and crop N uptake shows that the climatic conditions, crop characteristics (growth stage), the type, time and quantity of fertilizers applied are key factors affecting soil NO₃-N leaching in intensive leafy vegetable production systems. These factors previously studied under different

experimental conditions were observed using the 5TE sensors. Thus, we elucidated the applicability of a multiple function sensor as a non-destructive technique to monitor crop production-related issues geared towards sustainable agricultural development. In addition, the data obtained revealed that the soil N balance estimation system is a decision support tool for rational fertilizer application in intensive cropping systems and this study represents an evaluation of the state-of-art using primary data of commercial fields for vegetable.

REFERENCES

- Aimrun, W., Amin, M. S. M., Ezrin, M. H. 2009. Small scale spatial variability of apparent electrical conductivity within a paddy field. *Appl. Environ. Sci.* **2009**: 7.
- Allen, R. G. 2000. Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. *J. Hydrol.* **299**: 27–41.
- Allen, R. G., Pereira, L. S., Smith, M. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO irrigation and drainage paper 56, Rome. Food and Agriculture Organization of the United Nations, Rome, pp330.
- Asadi, M. E., Clemente, R. S. 2003. Evaluation of CERES-Maize of DSSAT model to simulate nitrate leaching, yield and soil moisture content under tropical conditions. *Food Agric. Environ.* **1**: 270–276.
- Bergström, L., Bowman, B. T., Sims, J. T. 2005. Definition of sustainable and unsustainable issues in nutrient management of modern agriculture. *Soil Use Manage.* **21**: 76–81.
- Chotangui, A. H., Sugahara, K., Torigoe, Y. 2013. Performance test of the soil nitrogen balance estimation system using lysimeter experiments in Andosols-based cropping system. *Environ. Control Biol.* **51**: 121–129.
- Christian, D. G., Riche, A. B. 1998. Nitrate leaching losses under *Miscanthus* grass planted on a silty clay loam soil. *Soil Use Manage.* **14**: 131–135.
- Di, H. J., Cameron, K. C. 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutr. Cycl. Agroecosyst.* **46**: 237–256.
- Eigenberg, R. A., Doran, J. W., Nienaber, J. A., Ferguson, R. B., Woodbury, B. L. 2002. Electrical conductivity monitoring of soil condition and available N with animal manure and cover crop. *Agric. Ecosyst. Environ.* **88**: 183–193.
- Higashi, N., Mori, Y., Inoue, M. 2005. Measurement of fertilizer leaching from the root zone using an automated infiltration soil water sampler in an unsaturated sandy field. *Soil. Sci. Plant. Nutr.* **51**: 1023–1033.
- Horiuchi, T. 2001. Sustainable soil managements in intensive crop cultivation — Organic matter supply and cropping system —. (in Japanese) *Jpn. J. Crop Sci.* **70**: 143–150. <http://www.decagon.com/assets/Manuals/5TE-Manual.pdf>
- Hu, K., Huang, Y., Li, H., Li B., Chen, D., White, R. E. 2005. Spatial variability of shallow groundwater level, electrical conductivity and nitrate concentration, and risk assessment of nitrate contamination in North China Plain. *Environ. Int.* **31**: 896–903.
- Ju, X. T., Kou, C. L., Christie, P., Dou, Z. X., Zhang, F. S. 2007. Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. *Environ. Pollut.* **145**: 497–506.
- Kobayashi, Y., Oshima, H., Hasegawa I., Niimi, H. 1995. Dynamics of Nitrogen in fields cultivated with forage crops in the warm and rainy region of Japan. (in Japanese with English summary) *Bull. Kyushu Agric. Exp. Stn.* **29**: 109–162.
- Krishnapillai, M., Ranjan, R. S. 2009. Non-destructive monitoring of nitrate concentration in a laboratory flow experiment using time domain reflectometry (TDR). *Environ. Technol.* **30**: 101–109.
- Kumazawa, K. 1999. Present state of nitrate pollution in groundwater. (in Japanese) *Jpn. Soc. Soil Sci. Plant Nutr.* **70**: 207–213.
- Luce, M. St., Whalen, J. K., Ziadi, N., Zebarth, B. J. 2011. Nitrogen dynamics and indices to predict soil nitrogen supply in humid temperate soils. *Adv. Agron.* **112**: 55–102.
- Ma, L., Ahuja, L. R., Ascough, J. C., Shaffer, M. J., Rojas, K. W., Malone, R. W., Cameira, M. R. 2001. Integrating system modeling with field research in agriculture: Applications of the root zone water quality model (RZWQM). *Adv. Agron.* **71**: 233–292.
- Maeda, M., Zhao, B., Ozaki, Y., Yoneyama, T. 2003. Nitrate leaching in an Andisol treated with different types of fertilizers. *Environ. Pollut.* **121**: 477–487.
- Matsuyama, N., Saigusa, M. 1994. Distribution of allophanic andosols and non-allophanic Andosols in Kanto and Chubu districts. *Jpn. J. Soil Sci. Plant Nutr.* **65**: 304–312.
- Mishima, S. 2001. Recent trend of nitrogen flow associated with agricultural production in Japan. *Soil Sci. Plant Nutr.* **47**: 157–166.
- Ogawa, Y., Ishikawa, M., Yoshihara, M., Ishikawa, M. 1979. Studies on nitrogen outflow from upland fields. (in Japanese) *Special Bull. Ibaraki Agric. Exp. Stn. Iss* **4**: 1–71.
- Parent, A., Anctil, F. 2012. Quantifying evapotranspiration of a rainfed potato crop in South-eastern Canada using eddy covariance techniques. *Agric. Water Manage.* **113**: 45–56.
- Patriquin, D. G., Blaikie, H., Patriquin, M. J., Yang, C. 1993. On-farm measurement of pH, electrical conductivity and nitrate in soil extracts for monitoring coupling and decoupling of nutrient cycles. *Biol. Agric. Hortic.* **9**: 231–272.
- Payero, J. O., Tarkalson, D. D., Irmak, S. 2006. Use of time domain reflectometry for continuous monitoring of nitrate-nitrogen in soil and water. *ASABE* **22**: 689–700.
- Persson, M., Dahlin, T. 2010. A profiling TDR probe for water content and electrical conductivity measurements of soils. *Eur. J. Soil Sci.* **61**: 1106–1112.
- Predotova, M., Bischoff, W., Buerkert, A. 2011. Mineral-nitrogen and phosphorus leaching from vegetable gardens in Niamey, Niger. *J. Plant Nutr. Soil Sci.* **174**: 47–55.
- Qiaogang, Y. U., Xuezhu, Y. E., Yingxu, C., Zhijian, Z., Guangming, T. 2008. Influences of nitrification inhibitor 3,4-dimethyl pyrazole phosphate on nitrogen and soil salt-ion leaching. *J. Environ. Sci.* **20**: 304–308.
- Schoolman, E. D., Jeremy, S. G., Kathleen, F. B., Andrew, R. B. 2011. How Interdisciplinary is Sustainability Research? Analyzing the structure of an emerging scientific field. *Sustain. Sci.* **7**: 67–80.
- Scudiero, E., Berti, A., Teatini, P., Morari, F. 2012. Simultaneous monitoring of soil water content and salinity with a low-cost capacitance-resistance probe. *Sensors* **12**: 17588–17607.
- Shibano, K., Ohno, Y. 1988. Evaluation of nitrate leaching in cabbage fields in relation to climatic factors. (in Japanese with English summary) *Bull. Natl. Inst. Veg. Orn. Plants Tea* **A-2**: 201–208.
- Shinjo, H., Kato, A., Fuji, K., Mori, K., Funakawa, S., Kosaki, T. 2006. Carbondioxide emission derived from soil organic matter decomposition and root respiration in Japanese forests under different ecological conditions. *Soil Plant Nutr.* **52**: 233–242.
- Stamatiadis, S. 1999. Field laboratory evaluation of soil quality

- changes resulting from injection of liquid sewage sludge. *App. Soil Ecol.* **12**: 263–272.
- Sugahara, K., Ueda, Y., Furue, K., Kusaba, T., Miura, K. 2003. Software system for soil nitrogen balance estimation on the internet. (in Japanese with English summary) *Bull. Agric. Res. Cent.* **3**: 99–105.
- Suzuki, K., Shiga, H. 2004. The maximum permissible amount of nitrogen input into an andisol upland field in Abashiri area assessed by percolate nitrate concentrations. (in Japanese with English summary) *Jpn. J. Soil Sci. Plant Nutr.* **75**: 45–52.
- Williams, J. R., Lord, E. I. 1997. The use of porous ceramic cup water samplers to measure solute leaching on chalk soils. *Soil Use Manage.* **13**: 156–162.
- Wraith, J. M., Das, B. S. 1998. Monitoring soil water and ionic solute distributions using time-domain reflectometry. *Soil Till. Res.* **47**: 145–150.
- Zupanc, V., Šturm, M., Lojen, S., Maršič-Kacjan, N., Adu-Gyamfi, J., Bračič-Čeleznik, B., Urbanc, J., Pintar, M. 2011. Nitrate leaching under vegetable field above a shallow aquifer in Slovenia. *Agric. Ecosyst. Environ.* **144**: 167–174.