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Full Length Research Paper

Nitrogen balance and dynamics as affected by water table and fertilization management in celery (*Apium graveolens*) cropping system of southwestern China

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There is a great concern on N cycle and dynamics in intensive cropping agricultural ecosystems because of their possible negative environmental consequences. Field experiments were conduced at the Dianchi catchment, Yunnan, China, to investigate the combined effects of groundwater table and N fertilization rate on gaseous N emissions, N leaching, and soil N accumulation, together with N uptake by celery in order to establish a budget of N inputs and N outputs in closed greenhouses. Treatments consisted of a combination of two water table levels: one with a water table depth of 2.0 m BLS (Below Land Surface) (Site A) and the other with a water table depth of 0.5 m BLS (Site B), and three N fertilizer application rates: 0 kg N ha^{-1} (no fertilization - NF), 450 kg N ha^{-1} (low fertilization - LF) and 1200 kg N ha^{-1} (high fertilization - HF) per rotation (about 90 d). Outputs of N were mainly as N uptake, with an average of 53.9% of total estimated output N. Crop N uptake significantly increased with an increase of N rate, but further fertilizer N inputs beyond 450 kg N ha^{-1} did not lead to significant increases in N uptake. The same N-fertilizer application rate produced different N balances with different water table levels. Compared with Site B, Site A reduced N leaching, gaseous N emissions, and soil N accumulation, while increased N uptake. The N balances indicate that N leaching into groundwater was comparatively low, while gaseous N emissions were the major loss pathway in the celery (*Apium graveolens*) cropping system, although both N leaching and gaseous N emissions decreased with the decrease of N-fertilizer rate and the increase of water table depth. Of these gaseous N emissions, NO/NO_2 was the highest, followed by N_2O and NH_3. In low N fertilization treatment, gaseous N emissions were reduced by 75 kg N ha^{-1}, N leaching by 8.4 kg N ha^{-1}, and soil N accumulation by 264 kg N ha^{-1} at Site A. Even LF had resulted in significant N losses at Site B. These findings suggest that the balanced fertilization both in optimizing crop yields and in minimizing its adverse impacts on environment should take into account depth of groundwater table.

Key words: Agricultural ecosystem, gaseous N emissions, N leaching

INTRODUCTION

There is a great concern about the impact of high input of fertilizer N on the N cycle in intensive cropping ecosystems (Richter and Roelcke, 2000). Increasing fertilizer N inputs to arable land beyond crop needs results in gaseous N emissions, N leaching into groundwater and N fluxes to surface water by runoff (Webb et al., 2000; Xing and Zhu, 2000), which may cause serious environmental problems. These potential problems include NO_3^- pollution of ground and surface waters (Foster et al., 1982; Guo et al., 2005), N_2O breakdown of stratospheric ozone (Crutzen, 1981), global warming (Duxbury and Mosier, 1993), NH_4^+ acidification of soil and N eutrophication of surface water body when deposited to land (Roelofs and Houdijk, 1991).

China consumed 23 million t of fertilizer N in 2000 (Anonymous, 2001), accounting for about 28% of total world N consumption (Fixen and West, 2002). The environmen-

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tal risk due to agricultural practices in China has become more and more serious. The N cycle and the fate of fertilizer N in agricultural system are receiving much attention from both agricultural and environmental scientists (Zhang et al., 1996; Zhu, 1997). Research on N balances that take into account N gaseous emissions, N leaching and soils inorganic N dynamics could provide more detailed information on the N cycles and losses by integrating soil N processes into total N budgets. Management of agricultural practices to minimize N pollution is dependent on developing an understanding of the agroecosystem. Despite considerable efforts to understand the fate of fertilizer-N (Zhang et al., 1992; Bhogal et al., 1997; Cai, 1997; Liu et al., 2001), many studies had focused on a single loss pathway. Thus, more understanding of the full N cycle in soil-crop systems should be promoted.

Because of its favorable climate, Kunming in the southwest of China has become one of the biggest localities for cropping flowers and vegetables. Excessive use of N fertilizer is very common in the flower and vegetable-cropping systems which aimed at maximizing crop output. At the Dianchi catchment, for example, the average N application rate was about 2 times more than the overall average in China (Guo et al., 2005). These rates exceeded N requirements of crops (Deng, 1998), and concomitantly lead to great losses of N with serious environmental consequences. Non-point source agricultural pollution has caused the eutrophication of Dianchi Lake, which has become a serious environmental problem in China (Guo et al., 2005). In 1994, for example, surface runoff caused by non-point source pollution contributed 2904 t total nitrogen and 407 t total phosphorus to the Dianchi Lake eutrophication, which was 53%, 54% of total N and P input to the lake, respectively (Yan, 1996). Nitrogen loss by NO_3^--N leaching from agricultural fields has been a growing concern as elevated NO_3^--N levels had been found in groundwater in many countries (Holden et al., 1992; Hamilton and Helsel, 1995; Zhang et al., 1996; Trauth and Xanthopoulos, 1997). In the Dianchi catchment, about 70% of groundwater was contaminated by NO_3^- with the NO_3-N of greater than 20 mg/L (Gao and Zhang, 2003). Guo et al. (2006) reported that N loading from celery-cropping sites to groundwater ranged from 15.2 to 316 kg N ha^{-1} a^{-1}, depending on the groundwater table and the N-fertilizer application rate.

There is a lack of in-situ integrated studies on N dynamics, N budgets and N loss pathways under high fertilizer N inputs in flower and vegetable-cropping systems. Integrated research is especially essential to understand N behavior and balance in specific cropping system with different groundwater tables and different N application rates. In this study, we investigated the effects of the amount of applied N-fertilizer traditionally used by farmers in the region (about 1,200 kg N ha^{-1} per rotation) and three-eighth of this amount (450 kg N ha^{-1} per rotation, regarded as the balanced fertilization amount) at two experimental sites with different groundwater tables on N dynamics. The goal of this study was to assist the development of strategies to minimize the environmental impact of N losses from agricultural land. A field study in closed greenhouses cultivating celery (*Apium graveolens*) in Dianchi catchment was performed to investigate:

- combined effects of water table and N application rate on N leaching, gaseous N emissions, crop N uptake and inorganic N changes in the soil
- N balance as related to the water table and the N application rate. The collected data was expected to give an evaluation of the potential for N losses from the crop-soil system.

MATERIALS AND METHODS

Experimental site

Experimental sites, located approximately 25 km southeast of Kunming city in southwestern China, are on the east Shore of Dianchi Lake, one of the biggest lakes in Yunnan province (Figure 1). The annual average temperature at this area is 14.7˚C with a maximum of 31˚C and minimum of -8.1˚C. Mean annual precipitation is 782.5 mm, more than ninety percent of which fell from May to October.

Site A is located near the foot of a highland with a groundwater table of 2.0 m BLS (Below Land Surface), while Site B was near the Shore of Dianchi Lake with a groundwater table of 0.5 m BLS (Figure 1). The pore medium was generally vertically heterogeneous and horizontally homogeneous at the experimental sites (Guo et al., 2006). The soil arable layer has high porosity with hydraulic conductivity of 10.4 m d^{-1} at Site A and 5.03 m d^{-1} at Site B. The soil texture was mainly clay at Site A, and silty clay at Site B. More detailed site information is provided by Guo et al. (2006). Due to intensive agricultural activities in the study area along with over-irrigation, groundwater is recharged mainly by vertical infiltration of irrigation water and partly by lateral penetration of water from the highland. Water generally flows from the highland and eventually discharges into the Dianchi Lake (DL) (Figure 1).

Crop management

Field experiments were conducted in two closed greenhouses (Site A and Site B, respectively). Each greenhouse has used for celery (*A. graveolens*) cropping. The experimental plot occupied an area of 30.0 × 4.0 m^2 within each greenhouse. Each greenhouse was divided into 8 subplots (1.8 × 7.0 m^2 for each), including HF (High Fertilization), LF (Low Fertilization), NF (No Fertilization) and CK (uncultivated control) treatments with two replicates for each. In order to avoid the interference among different treatments, the intervals between the boundaries of those treatments was not less than 0.5 m. Fertilization rates are presented in Table 1. Rates of N fertilizer as urea were 1,200 and 450 kg N ha^{-1} for one rotation (about 90 d), representing the traditional N rate used and the balanced fertilization N rate in this region, respectively. Fertilization was applied five times: one deep fertilization (10-15 cm depth) about 5 days before transplanting, and four top dressings at about 10, 30, 50, and 70 days after transplanting. The celery in all subplots was irrigated at the rate traditionally used by farmers in the region, once every three days, with approximately 28.6 mm each time (Figure 2). Guo et al. (2004) described the irrigation strategy in

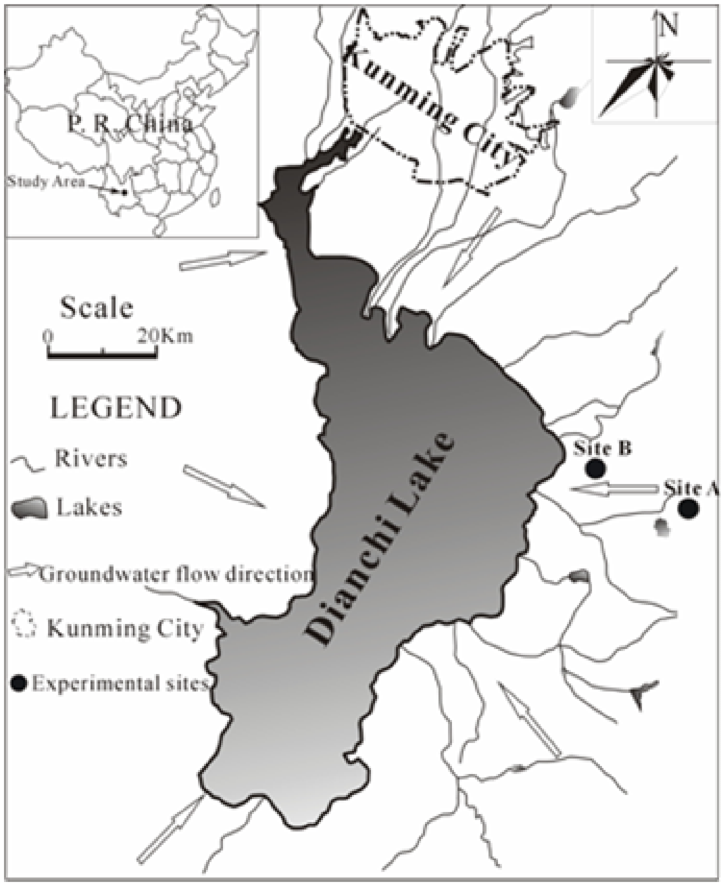

Figure 1. Study area and experimental sites in the Dianchi catchment, China

Table 1. Fertilization treatments per rotation (about 90 d)*.

	N (kg ha^{-1})[a]			P (kg ha^{-1})[b]			K (kg ha^{-1})[c]		
	CK/NF	LF	HF	CK/NF	LF	HF	CK/NF	LF	HF
Sum	0	450	1200	0	96.4	385.7	298.7	298.7	298.7
Deep fertilization	0	45	120	0	57.9	231.4	99.6	99.6	99.6
Top application	0	405	1080	0	38.6	154.3	199.1	199.1	199.1
1	0	40.5	108	0	7.7	30.9	24.9	24.9	24.9
2	0	81	216	0	15.4	61.7	49.8	49.8	49.8
3	0	162	432	0	15.4	61.7	74.7	74.7	74.7
4	0	121.5	324	0	0.0	0.0	49.8	49.8	49.8

* HF: High Fertilization; LF: Low Fertilization; NF: No Fertilization; CK: uncultivated control
[a] N-fertilizer was used as urea;
[b] P-fertilizer was used as concentrated super phosphate;
[c] K-fertilizer was used as potassium sulphate

more details. The land surrounding the experimental plots was irrigated similarly to minimize advection.

Nitrogen leaching

Prior to celery transplanting, TDR and tensiometers were installed. The TDR was used to monitor soil moisture with measured ranges of 0 and 60 % volumetric moisture content with an accuracy of ± 2% (Brandelik and Hubner, 1996; Musters and Bouten, 2000). The WM-1 was used to monitor matrix potential (Jing et al., 1994). Soil moisture and soil-water tension were measured once every day during the celery cultivation course.

Simultaneously, ceramic suction cups were set up at locations corresponding to the TDR and WM-1 tensiometers. In order to avoid disturbing the soil structure, the soils were carefully dug out and replaced at their original locations after installation of the experimental equipments. A well was installed at each experimental site to monitor the groundwater table level during the experiment.

Soil water was sampled generally once every week, and water

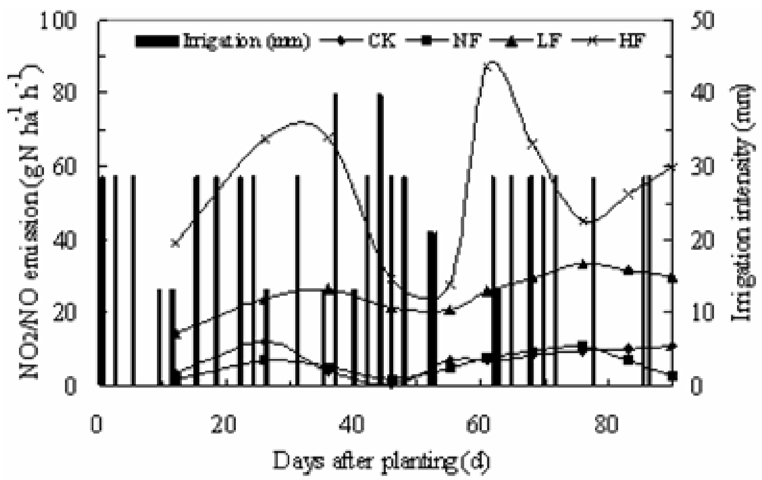

Figure 2. Irrigation intensity and NO/NO_2 emission at Site A during the study.

samples were collected in 650 ml glass bottles rinsed with deionised water just before use. The water samples were stored at 4ºC in a refrigerator. Concentrations of NO_3^-, NO_2^- and NH_4^+ were measured by colorimetry within one day after sampling (APHA, 1992).

The zero flux-plane method was used to calculate vertical infiltration recharge, based on the soil-water hydraulic theory that water flux does not exist when a gradient of total potential of soil-water is zero (Vachaud et al., 1978). On the zero flux planes, soil water complied with the following formula:

$$q = -K(\theta)\frac{\partial \phi}{\partial z} = 0 \tag{1}$$

Where q represents water flux; θ represents soil moisture content; K represents hydraulic conductivity; ϕ represents total potential of soil-water; z represents the depth.

Irrigation was generally uniform throughout the experimental site and the surface of the site was flat and horizontal, so horizontal flow of soil water was considered to be negligible. The vertical water equilibrium for the quantities is described by:

$$q(z) - q(z') = -\int_{z'}^{z} \frac{\partial \theta}{\partial t} dz \tag{2}$$

$$Q(z) - Q(z') = \int_{z'}^{z} \theta(z, t_1) dz - \int_{z'}^{z} \theta(z, t_2) dz \tag{3}$$

where $q(z)$ and $q(z')$ represent the water flux at depths z and z', respectively; $Q(z)$ and $Q(z')$ represent the quantity of water through the plane at depth of z and z', respectively; $\theta(z,t_1)$ and $\theta(z,t_2)$ represent volumetric moisture content of soil at t_1 and t_2, respectively.

When the zero flux planes was at a depth of z', $q(z')$ and $Q(z')$ were equal to zero, equations 2 and 3 could be simplified as:

$$q(z) = -\int_{z'}^{z} \frac{\partial \theta}{\partial t} dz \tag{4}$$

$$Q(z) = \int_{z'}^{z} \theta(z, t_1) dz - \int_{z'}^{z} \theta(z, t_2) dz \tag{5}$$

In case that the zero fluxes planes existed, the amounts of N leaching (L_N) into groundwater at water table, were obtained from the equation:

$$L_N = Q(z) C_Z \tag{6}$$

Where $Q(z)$ was the water flowing calculated at water table (z) from the zero flux plane method and C_Z was N concentration in the soil solution sampled by suction cups near the groundwater table. The detailed description of calculation process can be found in Guo et al. (2006). N leaching between sampling dates was estimated using the trapezoidal rule, i.e. linear interpolation between sampling points (Lord and Shepherd, 1993). Summarizing these for all sampling occasions gave total N leaching in each subplot

N_2O, NO/NO_2 and NH_3 emissions

N_2O

Movable polymethyl methacrylate chambers of one cubic meter (1 × 1 × 1 m^3), with an inlet on a side and an outlet on other side, and a sampling port on the top, were used to sample gaseous N fluxes emitting from the soil surface. The outlet of the chamber was located on a higher level than the inlet (Figure 3). Before sampling, gas tightness test of the chamber was checked to make sure the gas emission of N_2O was linear within 30 min. Two subsamples for N_2O analysis were collected from the sampling tube when all ports connected to the chambers had been closed for 0 and 30 min, respectively. The 100 ml gas sample was collected using a 50 ml syringe (filled twice) and injected into an airtight gasbag, and transported to the laboratory for analysis.

Analysis of N_2O was carried out using a GC-14A (Shimadzu Co. Japan) fitted with a backflush inlet system, a 3.5 m × 3.2 mm stain-

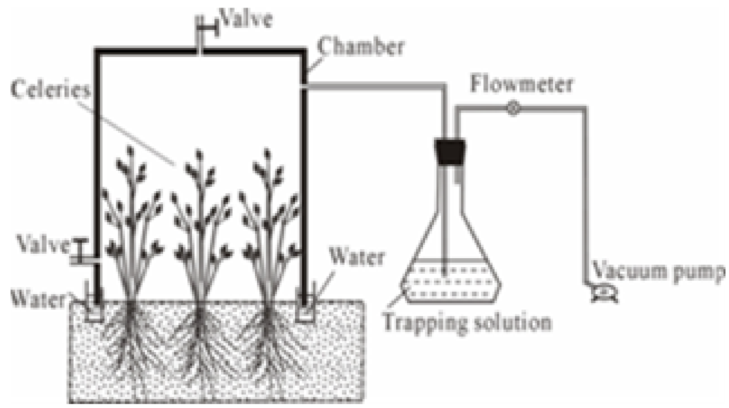

Figure 3. Sketch drawing of the gaseous N collector used in this study (The pump and trapping system were only used for NO/NO_2 sampling).

less steel column packed with Porapak QS (80-100 mesh) operated at 60˚C. The temperatures of the electron capture detector and the injector were 300 and 100˚C, respectively. The carrier gas was super pure N_2 at a flow rate of 60 ml min^{-1}. The standard N_2O was provided by National Research Center for Standard Substances (China) and calibrated by the standard N_2O granted by Atmosphere Institute of the Australian Commonwealth Scientific and Industrial Research Organization. N_2O emission was calculated by the difference of N_2O concentration in the two sub samples.

NO/NO_2

The same chambers as used for N_2O were adapted to collect NO/NO_2. A vacuum pump was used to control the gas flow rate in the trapping system. After chamber air passed through an oxidizing tube packed with $KMnO_4$-rinsing silica sand, the gas was trapped in a volumetric flask containing 50 ml of 10 g L^{-1} (1-Naphthyl)-ethylenediamine dihydrochloride solution. The gas was trapped for 30 min at a flow rate of 0.2 L min^{-1}. NO/NO_2 emission was calculated according to NO_2^- concentration in the trapping solution. It was measured colorimetrically by the Griess-Saltzman method (APHA, 1992).

NH_3

The method for monitoring NH_3 emission was similar to that for NO/NO_2. The trapping solution for fixing NH_3 was 0.01 N H_2SO_4. The gas reacted with the trapping solution for 30 min at a flow rate of 1.0 L min^{-1}. NH_3 emission was evaluated by NH_4^+ concentration in the trapping solution measured by the Nessler's reagent colorimetric method (China EPA, 1997).

All gaseous N emissions were generally monitored once every 6-14 days during celery cropping. All data were plotted against time and a linear extrapolation was carried out between sampling dates. The cumulative area of the resultant joined peaks was then calculated and expressed as the emission in kg N ha^{-1}.

Nitrogen uptake by harvested celery

At celery maturity, three plants were randomly sampled in each subplot. The fresh aboveground biomass was weighed immediately after sampling. The plants per subplot were washed with Milli-Q water to remove soil particles, pooled, dried for 48 h at 65 ˚C and ground to 0.2 mm for total N analysis by the Kjeldahl method (Bremner, 1996) and the amount of N uptake by celery shoots was calculated.

Soil N

In order to compare soil N concentrations at the beginning and end of the study, soil samples were taken at different depths down to the groundwater table using a steel cylindrical auger (ID 42 mm) just before planting and after harvest. In each subplot, three sampling points were randomly selected at each sampling time and the samples from the same depth were fully mixed. TIN (Total Inorganic N), NH_4^+-N and NO_3^--N were extracted by shaking 40 g mixed moist soil with 200 ml 2 M KCl for 2 h. The soil suspension was centrifuged (4000 rpm for 20 min) and filtered through a 0.45 µm cellulose acetate filter. The filtrate was directly analyzed for TIN, NH_4^+-N and NO_3^--N by colorimetry methods (APHA, 1992).

RESULTS AND DISCUSSION

Nitrogen leaching

Nitrogen leaching to groundwater under different subplots was calculated according to Equation 6 and discussed in details by Guo et al. (2006). Nitrate was the dominant N component entering groundwater from the vadose zone (Table 2), as expected from other studies (Webster et al., 1993; Kraft and Stites, 2003). This is probably because the NO_2^- is normally an unstable anionic group while NH_4^+ is mostly adsorbed on the clay minerals and organic matter radicals. A modest groundwater quality goal might be of NO_3^--N concentration that does not exceed the 10 mg L^{-1} MCL (Maximum Contaminant Level). One way to attain this goal is to dilute the NO_3^- in groundwater recharge from crop fields with NO_3^--free recharge from other land uses (Stites and Kraft, 2001). Given the annual groundwater recharge rate of 300 mm, NO_3^--N leaching greater than 30 kg ha^{-1} a^{-1} will cause average groundwater quality to exceed MCL. In case of four celery rotations

Table 2. N leaching to groundwater under different treatments during one rotation (kg N ha^{-1}).

Treatment*		NO_3^--N leaching	NO_2^--N leaching	NH_4^+-N leaching	Sum	N-Fertilizer applied	Percentage of N leaching to applied fertilizer N (%)
Site A	HF	11.8	0.31	0.07	12.18	1200	1.01
	LF	3.4	0.10	0.34	3.84	450	0.85
	NF	2.5	0.10	0.09	2.69	-	-
	CK	5.4	0.18	0.08	5.66	-	-
Site B	HF	78.0	0.19	0.88	79.07	1200	6.58
	LF	55.3	0.16	0.49	55.95	450	12.4
	NF	37.5	0.09	0.80	38.39	-	-
	CK	16.5	0.14	0.58	17.22	-	-

Site A was located near the foot of highland with a groundwater water of 2.0 m BLS (Below Land Surface), while Site B near the shore of Dianchi Lake with a groundwater table of 0.5 m BLS; HF: High Fertilization; LF: Low Fertilization; NF: No Fertilization; CK: uncultivated control.

Table 3. Gaseous N emissions from different treatments during one rotation (kg N ha^{-1})*.

Treatment	NH_3		$NO+NO_2$		N_2O	
	Site A	**Site B**	**Site A**	**Site B**	**Site A**	**Site B**
HF	0.74	22.8	123	160	15.5	19.0
LF	0.37	8.6	56.0	72.0	8.1	11.0
NF	0.14	4.0	11.9	21.1	4.0	5.4
CK	0.09	2.6	15.8	13.5	3.0	4.7

* Site A was located near the foot of highland with a groundwater water of 2.0 m BLS, while Site B near the shore of Dianchi Lake with a groundwater table of 0.5 m BLS; HF: High Fertilization; LF: Low Fertilization; NF: No Fertilization; CK: uncultivated control.

in each year, annual NO_3^- leaching was expected to be 221 and 312 kg ha^{-1} in LF and HF of Site B, respectively, which were seven to ten times the MCL. Therefore, each hectare of irrigated celery at the lowland would require 7 to 10 ha of land uses with no NO_3^- loading to meet even this modest groundwater quality goal.

With regard to the same groundwater table, the NO_3^--N leaching under HF was higher than that under LF. It indicates that application of excessive amounts of N fertilizers would result in severe loss of NO_3^--N with an increasing contamination of groundwater. These observations confirm the results of Granlund et al. (2000) who found that NO_3^- leaching increased with increasing N-fertilization rates.

For HF, NO_3^--N leaching at Site B was 5.6 times more than that at Site A, indicating groundwater table significantly controlled the accumulation of NO_3^- at the vadose zone and eventually percolation to groundwater. In similar hydrogeological settings, shallow water table favoured nitrate movement to groundwater. Delin and London (2002) also observed that the mass fluxes of NO_3^- and Cl^- to the water table were 2-5 times greater, respectively, at the lowland site compared to the upland site.

Although there was no N fertilizer applied to CK and NF, NO_3^--N leaching at these treatments was of significance in deteriorating groundwater quality (Table 2). At Site A, higher NO_3^- leaching in CK than in NF was found. This phenomenon generally arose from the leaching of high NO_3^- amount of arable soils even without cultivation. Consequently, surface covering would decrease pollution of groundwater.

Gaseous N emissions

At both Site A and Site B, N_2O emission was the highest in HF, generally followed the order LF>NF>CK (Table 3). This trend indicates that the N fertilizer application increased N_2O emission (Figure 4). In this respect, Bouwman (1990) also observed increases in N_2O emissions with increasing amounts of N fertilizers. Similar results were found by Eichner, (1990), Mosier et al. (1991) and Sitaula et al. (1995) who related this phenomenon to supplying the substrate for nitrification and denitrification processes by organic and chemical fertilization. Nitrous oxide emission from Site B was higher than from Site A, possibly due to higher moisture content of 46% in the arable soil at Site B with a shallow groundwater level in comparison with Site A with a deep groundwater level (40%). The high moisture content decreased gas diffusivity and consequently contributed to increased N_2O emission. Smith et al. (1998) observed exponential relationship between N_2O flux and water-filled pore space. In the

Table 4. N input, crop yield, N uptake and fertilizer utilization efficiency during one rotation*.

Treatment	Site A			Site B		
	NF	LF	HF	NF	LF	HF
Fertilizer N (kg N ha^{-1})	0	450	1200	0	450	1200
Dry crop yield (t ha^{-1})	3.7	5.7	4.7	3.1	3.7	3.8
N uptake (kg N ha^{-1})	124	137	138	89.0	93.5	102
Utilization efficiency (%)	-	30.4	11.5	-	20.8	8.49

Site A was located near the foot of highland with a groundwater water of 2.0 m BLS, while Site B near the shore of Dianchi Lake with a groundwater table of 0.5 m BLS; HF: High Fertilization; LF: Low Fertilization; NF: No Fertilization

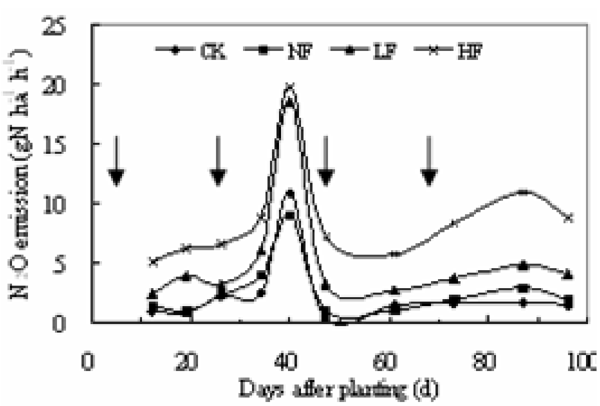

Figure 4. The variation in N_2O emission at Site B during the study. Solid arrows denote fertilizer N application.

current study, the peak of N_2O emission of 6.38 and 19.7 g N $ha^{-1}·h^{-1}$ occurred after 216 kg N ha^{-1} was applied in HF of Site A and HF of Site B, respectively, as well as 39.9 mm of irrigation. It seems that intense nitrification and denitrification activity with increased N_2O production would be promoted by both N fertilizer application and intensive irrigation, which is expected to increase anaerobic soil conditions.

Intensities of NH_3 and NO/NO_2 emissions followed the order HF>LF>NF>CK in each experimental site (Table 3). In contrast to N_2O, NH_3 flux from Site B was much greater than from Site A. Possibly, the difference in NH_3 emission between Site A and Site B was due to the different moisture contents between the working sites. In general, NH_3 flux was relatively small.

Of these gaseous N emissions, NO/NO_2 was the highest with the value of 123 and 160 kg N ha^{-1} in case of HF of Sites A and B, respectively. Wolf and Russow (2000) also found that the emission of NO exceeded the emission of N_2O by up to 20 fold due to microbial oxidation processes. As seen in Figure 2, in comparison with a high irrigation frequency, NO/NO_2 emission was much greater in a low irrigation frequency at Site A. Especially for HF, the emission increased from 39.1 to 67.9 g N ha^{-1} h^{-1} with a decrease of the irrigation frequency from once every three days to once every five days. Additionally, after no irrigation was carried out for 7 days, the emission in HF was up to 87.6 g N ha^{-1} h^{-1}. It seems that nitrification was possibly the dominant process for production of NO/NO_2.

Crop yield and N content

The results (Table 4) showed that dry crop yields of Site A were 19.4, 54.1 and 23.7% higher than at Site B in NF, LF and HF, respectively. The differences here were significant, illustrating that higher water table adversely affected crop yields. In contrast, Tan et al. (1996) obtained lower corn grain yields on a sandy loam soil with a water table depth of 0.8 m compared with 0.6 m. They related the unexpected result to reduced stomatal conductance and transpiration rates caused by water stress. Crop type, soil nutrition, and crop management may also be involved in this contradiction.

For both the experimental sites, the results showed no significant difference in celery yields between the two N application rates (LF and HF). Addition of 1200 kg N ha^{-1} is beyond the N requirement of the celery, and fertilization rate can be minimized to a reasonable value at which crop yield would be at its maximum value without excessive application of fertilizer-N (Bučienė et al., 2003).

The N uptake as indexed by yield total N was found higher with HF, which was recorded up to 138 and 102 kg N ha^{-1} at Sites A and B, respectively. Although largest amount of N was taken up in case of HF, utilization efficiencies of N-fertilizer were found relatively low, with 11.5 and 8.49% at Sites A and B, respectively. In contrast to HF, N fertilizer utilization efficiencies in LF were much higher, exceeding 30% at Site A. This demonstrates that high N fertilization may increase N pollution.

Nitrogen in the soil

Initial soil inorganic N in the arable layer was 2.12 and 1.73 mg g^{-1} at Site A and Site B, respectively. Such difference may be due to soil type, soil C and soil N, tending to be greater in soils of higher clay content (Stevenson, 1982). This work showed that organic matter content in the arable layer of Site A was 3.10%, which was higher

Table 5. Initial soil N concentrations and their increases after one rotation in the arable soils (the surface soils above 30 cm below land surface) *.

		Initial N (kg N ha^{-1})	Increases of N in surface soil (kg N ha^{-1}) [a]			
			CK	NF	LF	HF
Site A	TIN [b]	6000	-85.0	-166	198	462
	NH_4^+-N	145	-19.6	-35.3	9.7	74.8
	NO_3^--N	353	-82.0	-123	66	487
Site B	TIN	5060	-58.3	-169	192	775
	NH_4^+-N	251	-5.8	-36.5	58.3	106
	NO_3^--N	153	-41.5	-84.5	83.8	615

* Site A was located near the foot of highland with a groundwater water of 2.0 m BLS, while Site B near the shore of Dianchi Lake with a groundwater table of 0.5 m BLS; HF: High Fertilization; LF: Low Fertilization; NF: No Fertilization; CK: uncultivated control.
[a] Negatives indicate soil N decreased
[b] Total Inorganic Nitrogen

than that of Site B (2.00%). The soil inorganic N concentrations measured before the experiments were equivalent to 6000 and 5060 kg N ha^{-1} at Sites A and B, respectively, in the depth of 30 cm and soil dry bulk densities of 1.23 and 1.30 g cm^{-3} for Sites A and B, respectively (Table 5). However, for both experimental sites, the sums of NH_4^+-N and NO_3^--N were much lower than soil TIN, which was possibly due to the presence of nitrite in the arable soils.

The increases of NO_3^--N in the arable soils were 615 and 83.8 kg N ha^{-1} in cases of HF and LF of Site B, respectively, which were a little greater than those in HF and LF of Site A, with values of 487 and 66.0 kg N ha^{-1}, respectively. The increases of NO_3^--N resulted in high levels of residual soil NO_3^--N after harvest, increasing the risk of movement to groundwater. When evapotranspiration was low and irrigation exceeded the water holding capacity of the soil, residual NO_3^--N could leach beyond the crop root zones with percolating water. It was, however, interesting to note that in CK, significant reduction of NO_3^--N in the arable soils was observed to be consistent with the relatively high NO_3^- leaching (Table 5). This phenomenon would result from leaching of the NO_3^- and denitrification processes in arable soils even without cultivation of celery especially in case of regular irrigation. In general, the decreases of NO_3^--N was beyond the values recorded at the start of the experiment when no fertilizer N was applied in both sites. This deficit in soil NO_3^--N could be compensated by mineralization of organic N which formerly remained in the soils.

Table 5 also demonstrates that soil TIN, NH_4^+-N and NO_3^--N in the arable soils increased in cases of HF and LF, and decreased in NF and CK in both sites. In both NF and CK, N leaching, gaseous N emissions, microbial N-immobilization, and/or crop uptake decreased N in the arable soils. The amount of N-fertilizer applied in both HF and LF seems to exceed crop N demand and resulted in surplus N-content. Especially in case of HF, the increase of TIN in the arable soils was up to 462 and 775 kg N ha^{-1} at Sites A and B, respectively.

Effect of water table and fertilization management on N balance

From the sustainable land use point of view, agricultural nutrient budgets must be in balance to avoid negative impacts on the environment especially in extensive agricultural systems. We therefore calculated the N budget for all of the treatment locations from the top 30 cm soil layer, taking into account crop N uptake, soil N accumulation, N leaching and gaseous N emissions. The results are presented in Table 6. Because the experiments were carried out in the closed greenhouses, wet N deposition due to rainfall was not included in the N inputs. As seem in Table 6, most of applied N was kept in the arable soils in both LF and HF at Sites A and B. The maximum amount of N remaining in the arable soils was found in HF at Site B, which was 775 kg N ha^{-1} (equivalent to 64.5% of input fertilizer-N).

Outputs of N were considered mainly as N uptake by crops which ranged from 38.8 % of the total estimated N outputs in LF of Site B to 86.9 % of the total in NF of Site A. The exception happened in HF of Site B where N uptake only accounted for 26.6% of the total estimated outputs. An average of 53.9% of the estimated N outputs was accounted for by crop uptake. However, the large differences in the proportions of N uptake caused by the differences in groundwater table and fertilization rate are expected to be mostly related to water level and nutrition conditions of crop growth in the arable soils. For example, with application of the same amount of N-fertilizer, both crop yields and N uptake at Site A were greater than at Site B (Table 4). Therefore, properly lowering water table would increase celery yield with increased N output through celery from the crop-soil system. Crop N uptake significantly increased with an increase of N fertilization rate, but further fertilizer-N application beyond 450 kg N ha^{-1} did not lead to significant increases in crop yield (Table 6). The weak response of crop N uptake to higher N application rate indicates that the increased fertilizer N was poorly utilized by celery, as crop yields did not have

Table 6. Balance of N inputs and outputs in each treatment during one celery rotation (kg N ha^{-1}) *.

<table>
<tr><th colspan="3" rowspan="2"></th><th colspan="4">Site A</th><th colspan="4">Site B</th></tr>
<tr><th>CK</th><th>NF</th><th>LF</th><th>HF</th><th>CK</th><th>NF</th><th>LF</th><th>HF</th></tr>
<tr><td rowspan="6">Output N</td><td colspan="2">N leaching</td><td>5.60</td><td>2.68</td><td>3.80</td><td>12.2</td><td>17.2</td><td>38.3</td><td>56.0</td><td>79.0</td></tr>
<tr><td rowspan="3">Gaseous N</td><td>NH_3</td><td>0.09</td><td>0.14</td><td>0.37</td><td>0.74</td><td>2.57</td><td>3.95</td><td>8.57</td><td>22.8</td></tr>
<tr><td>$NO+NO_2$</td><td>15.8</td><td>11.9</td><td>55.9</td><td>122</td><td>13.5</td><td>21.0</td><td>72. 1</td><td>160</td></tr>
<tr><td>N_2O</td><td>2.95</td><td>3.97</td><td>8.04</td><td>15.5</td><td>4.70</td><td>5.43</td><td>11. 0</td><td>19.0</td></tr>
<tr><td colspan="2">Total Gaseous N emissions</td><td>18.8</td><td>16.0</td><td>64.3</td><td>139</td><td>20.7</td><td>30.4</td><td>91.7</td><td>202</td></tr>
<tr><td colspan="2">N uptake</td><td>0</td><td>124</td><td>137</td><td>138</td><td>0</td><td>89.0</td><td>93.5</td><td>102</td></tr>
<tr><td colspan="3">Total monitored output N</td><td>24.4</td><td>143</td><td>205</td><td>289</td><td>38.0</td><td>158</td><td>241</td><td>382</td></tr>
<tr><td colspan="3">N retained in arable soils [a]</td><td>-85.0</td><td>-166</td><td>198</td><td>461</td><td>-58.3</td><td>-169</td><td>193</td><td>774</td></tr>
<tr><td colspan="3">Input N</td><td>0</td><td>0</td><td>450</td><td>1200</td><td>0</td><td>0</td><td>450</td><td>1200</td></tr>
<tr><td colspan="3">Offset of N balance</td><td>60.5</td><td>23.3</td><td>47.0</td><td>450</td><td>20.4</td><td>11.5</td><td>16.3</td><td>44.1</td></tr>
</table>

* Site A was located near the foot of highland with a groundwater water of 2.0 m BLS, while Site B near the shore of Dianchi Lake with a groundwater table of 0.5 m BLS; HF: High Fertilization; LF: Low Fertilization; NF: No Fertilization; CK: uncultivated control
[a] Negatives indicated soil N decreased in the arable soils

a big difference between LF and HF (Table 4). The lower rate of N applied in LF treatments prevented large N fertilizer loss by matching crop N requirement better than in case of high N-fertilization.

Although the amount of gaseous N emissions were lower than N uptake in LF of Site A, they approached N uptake of HF of Site A and LF of Site B. Gaseous N emissions from Site B, HF, were greater than the amount of N taken up by celery. In general, gaseous N emissions were the major component of N outputs, which accounted for 31.4-52.7% of total estimated output N. At the same Site, gaseous N emissions in HF were observed to be larger than in LF, indicating that N-fertilizer application was the major factor in increasing gaseous N emissions. Furthermore, gaseous N emissions increased with the decrease of the depth of groundwater table, recorded in the study from 64.2 kg N ha^{-1} in LF of Site A to 91.6 kg N ha^{-1} in LF of Site B.

Of N outputs, N leaching was found to be the lowest. At Site A, N leaching was 0.85 and 1.01% of N input for LF and HF, respectively. In general, the decreases in N leaching with increase of water table depth were observed in both HF and LF, and were more pronounced than the gaseous N emissions. This illustrates that the groundwater water table would more efficiently be used to control N leaching into groundwater than gaseous N emissions. In the current study, N leaching from LF of Site B was 14 times greater than from LF of Site A.

At Site B, N leaching and gaseous N emissions were both important in HF and LF. The sum of N leaching and gaseous N emissions accounted for 23.4 and 32.8% of the amount of fertilizer-N added in LF and HF, respecttively. This indicates that groundwater and atmosphere were very vulnerable to contamination by cultivation at the areas with shallow groundwater tables. Although low N-fertilizer application rate was performed at Site B (450 kg N ha^{-1}), total gaseous N emissions and N leaching were up to 91.6 and 55.8 kg N ha^{-1}, respectively.

The offsets of N balances were observed in all treatments (Table 6). These offsets were possibly due to N_2 loss and downward movement of soil N from the arable soils to depths below 30 cm BLS. Cai et al. (2001) and Ruckauf et al. (2004) found that N_2 emission was about 2-4 times higher than N_2O emission in soil with moisture content adjusted at 70% of its water holding capacity and more than 10 times in the flooded soils. From these studies we estimate that N_2 emissions ranged from 31 to 62 kg N ha^{-1} in HF of Site A, and from 38 to 76 kg N ha^{-1} in HF of Site B. The results show that the amount of N retained in the vadose zone at Site A was greater than at Site B in case of the two fertilization rates. The greater amount of N accumulated in the vadose zone at Site A seems to be a consequence of the thicker vadose zone which facilitated the storage of N having passed beyond the arable soil.

Conclusion

Both water table and fertilization management significantly affected crop yields, N uptake, soil N accumulation and N losses. Nitrogen utilization efficiency greatly decreased with the increase of N-fertilizer application rate and the decrease of water table depth. The high water table increased N loss by leaching, and then decreased N accumulation in the soil profile. Increasing fertilizer N inputs beyond crop needs resulted in great increases in N gaseous emissions, N leaching into groundwater, soil N accumulation, and N flux to surface water by runoff, which may cause serious environmental problems.

The low N fertilization rate at Site A was the most effecttive in reducing gaseous N emissions, N leaching and soil N accumulation, while in maintaining good crop yields. Soil N accumulated in the arable soils was the greatest among all parts of the N budgets in the treatments with N-fertilizer application. From the sustainable land use point of view, agricultural nutrient budgets must be in balance to avoid negative impacts on the environment, especially in intensive agricultural systems.

The N balance calculations indicate that N leaching into groundwater was comparatively small (1.86~4.21% of total estimated N outputs at Site A), while gaseous N emissions (including N_2O, NH_3 and NO/NO_2) were the major N losses (31.4~48.0%) in the celery cropping system. Due to their various negative effects on ecosystem and human health, more concern should be taken to control their emissions. In general, the precise estimation of N fertilizer needs of crops should be required to minimize gaseous N emissions and N leaching. The traditional N rates practiced by farmers in the studied area exceeded the crop N requirement. A 62.5% reduction in fertilizer N on the basis of conventional N application (1200 kg N ha^{-1}) still maintained high crop yields, improved agronomic N-use efficiency and minimized NO_3-N accumulation in the soil profile. By simply matching fertilizer N input to crop demand shows the potential for developing environmentally friendly agriculture.

The same N-fertilizer application rate produced different N balances with the different water table depths. The low N fertilization rate, regarded as balanced fertilization in the region was the most effective in reducing gaseous N emissions, N leaching and soil N accumulation, and in maintaining good crop yields at Site A which had deep water table of 2.0 m BLS, while resulted in significant N losses (including gaseous N emissions and N leaching) in Site B LF where the shallow water table was only 0.5 m BLS. These data demonstrate the negative consequences of high water table on environmental soundness and agricultural sustainability.

Therefore, both water table management and optimization of N application rate may be considered as an economic means to offer environmental benefits. These benefits are accomplished by reducing gaseous N emissions which contribute to global warming and destruction of stratospheric ozone and by decreasing N leaching. Specific balanced fertilization taking into account soil nutrition status and texture, depth of groundwater table, climatic conditions, and crop type, would both optimize crop yield and minimize its adverse impacts on environment.

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