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Eco-restoration: Simultaneous nutrient removal from soil and water in a complex residential–cropland area

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A promising and environmentally benign integrated eco-restoration technology has proven highly effective for simultaneously removing nutrients from soil and water, decreasing the output of nutrient, and reducing eutrophic risk of surface waters.

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ABSTRACT

An eco-restoration system to remove excess nutrients and restore the agricultural ecosystem balance was proposed and applied from August 2006 to August 2008 in a residential–cropland complex area (1.4×10^5 m^2) in Kunming, western China, where the self-purifying capacity of the agricultural ecosystem had been lost. The proposed eco-restoration system examined includes three main foci: farming management, bioremediation, and wastewater treatment. The results showed that the removal efficiencies of total phosphorus (TP) and total nitrogen (TN) from the complex wastewater were 83% and 88%, respectively. The Simpson's diversity indices of macrophytes and zoobenthos indicated that the system had increased macrophyte and zoobenthic diversity as well as improved growth conditions of the plankton habitats. The results demonstrated that the proposed eco-restoration system is a promising approach for decreasing the output of nutrients from soil, improving agricultural ecosystem health, and minimizing the downstream eutrophication risk for surface waters.

1. Introduction

One of the most important pollution sources causing eutrophication of surface water in rural areas is agricultural non-point-source pollutants (Tilman et al., 2002). These non-point-source pollutants are carried by runoff and enter surface water during rain events, causing eutrophication (Tilman et al., 2001; Pan et al., 2010). Another important source causing eutrophication is that of the diffuse pollutants (often domestic wastewater discharged by local communities) that flow into downstream waters in rural areas (Tilman et al., 2002). Thus, it is important to simultaneously remove pollutants from soil and water (wastewater) in rural areas.

Many measures based on ecological engineering have been proposed to control agricultural non-point-source pollution. For instance, multilevel biopond systems, constructed cushion zones, constructed wetlands or soil-infiltration systems are often applied (Rode et al., 2009). However, these technologies focus on treating rather than preventing agricultural non-point-source pollution. Moreover, traditional wastewater treatment facilities are obviously inadequate to collect and treat non-point-source pollutants (USEPA, 1989). A system to collect and remove pollutants simultaneously from complex residential–cropland areas should be considered.

To date, various technologies for the treatment of rural domestic wastewater have been developed. These can be summarized into four groups. The first is based on soil-filtration, which includes slow-infiltration land-treatment systems (Schaub et al., 1982), rapid soil-infiltration systems (Huthins et al., 1983), sand-filter systems (Urynowicz et al., 2007), constructed wetlands (Dong et al., 2005), capillary-barrier infiltration systems (Yang et al., 2004), and earthworm-amended soil filters (Nahmani et al., 2007; Costello and Lamberti, 2009). The second group is biotoilet systems, which are used quite widely in Japan (Angel and Naoyuki, 2005). The third group is centralized municipal wastewater treatment systems based on anaerobic/aerobic (A/O) processes (Zhang and Gao, 2000). The fourth group consists of sorption-treatment systems based on sorbents such as active carbon or ceramsite (Taraba et al., 1990). Although these single technologies show high-efficiency in treating domestic wastewater, they can't restrain the pollutant (including excess nutrients) release from soil to water.

Combining the following two basic principles, a multilevel eco-restoration system in agricultural ecosystem was proposed. The first principle is ecological stoichiometry, that is, an approach that

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analyzes the constraints and consequences of the mass balances of multiple chemical elements, such as nitrogen and phosphorus in ecological interactions (Elser and Urabe, 1999). This would involve reducing the input of fertilizer to the cropland and decreasing the output of nutrient from the residential–cropland complex area. The second is ecological restoration and pollutant minimization, which involves renewing an unhealthy ecosystem through active human intervention (Yong et al., 2005). This could be achieved by planting macrophytes and adding sorbents (e.g., ceramsite) as well as managing and enhancing biofilm biomass via a constructed wetland.

Thus, we propose an eco-restoration model and use technology based on a three-part integrated eco-restoration system in order simultaneously to remove nutrients from soil and water in a complex residential–cropland area and transform the agricultural ecosystem into a healthy state. In the proposed bio-integrated solution, we believe the most important measure in nutrient level control is to restore the agricultural ecosystem to improve the function of the complex residential–cropland area. Three additional considerations should be taken into account: (1) There should be no potentially dangerous compounds or artificial materials put into the agricultural ecosystem; (2) the biodiversity in the contaminated ecosystem should be recovered and (3) the construction and daily running costs of the eco-restoration engineering project should be accepted by rural locals.

2. Materials and methods

2.1. Study area

The study area is a residential–cropland complex of 1.4×10^5 m^2, in the vicinity of the Dianchi Lake watershed, with a population of 780, in the suburbs of Kunming, southwestern China. The residential area, about 7.7×10^4 m^2, is surrounded by cropland, about 95% of which is planted with leeks, the remainder being used for growing flowers. The average annual input of fertilizer is 760 kg N/ha (as urea) and 100 kg P/ha (as superphosphate). The complex wastewater, consisting of domestic sewage, farming effluent and livestock wastewater is discharged directly onto the cropland. Alligator weed (*Alternanthera philoxeroides*) covered all drainage areas. The annual average water temperature is ~17–18 °C and the annual average rainfall is ~1000 mm (KMABDL, 2004).

2.2. Ecosystem management

The management of the ecosystem involved a 'three-pronged' approach to the problem. The first 'prong' involved farming management to decrease the input of nutrients into the cropland. Two measures were conducted overall the cropland by local farmers under our instruction. The first measure was the use of sulfur (S) and dicyandiamide (DCD) in lieu of part of the normally applied urea so as to decrease volatile nitrogen loss. According to the assessment of S and DCD application, the amounts applied to the leek cropland are environmentally and food safe (Pang, 2007). The second measure was the use of duckweed (*Spirodela polyrhiza*). Duckweed was cultivated in the interchannel water to reduce the amount of fertilizer and nutrients present. Half of this duckweed was collected every 15 days and returned to the leek crop as a green manure after drying to a 50–60% moisture level. The total cultivated area of duckweed was 7800 m^2. It was estimated that 1.18×10^3 kg of dried duckweed at 50–60% moisture was returned to the soil over the course of the experiment.

The second 'prong' involved a bioremediation program consisting of a deposition pool with a volume of 250 m^3 and an ecological ditch system, which was designed to treat complex wastewater, with average loads of about 500 m^3/d on the dry days. The ecological ditch included two parts: one, in the leek cropland, comprised 14 ecological channels of the same length (100 m) and of an average width of 1.0 m and of water depth from 0.2 to 0.9 m (soil-wall gradient 55°); the other was adjacent to the cropland and comprised one ecological trunk channel with a total length of 550 m, an average width of 2.5 m and water depth from 0.4 to 1.3 m (soil-wall gradient 45°). The high-productivity macrophytes, *Scirpus tabernaemontani*, *Canna indica*, *Zizania latifolia*, *Juncus minimus*, *Cyperus alternifolius*, *Zantedeschia aethiopica* Spreng, and *Acorus calamus* Linn. were planted along both walls of the ecological channels and the ecological trunk channel at intervals of 0.5 m. The ecological channel was almost covered by the macrophytes after three months. A series of 0.04-m^3 nylon tanks containing an adsorbent, ceramsite (Kunming Yongle Building Co.), were placed on the bottom of the ecological trunk channel at intervals of 2.0 m for the adsorption of pollutants from the wastewater.

The last 'prong' was wastewater treatment, the main facility of which involved the construction of a 240-m^2 artificial wetland to further purify the effluent from the ecological ditches. There were three different gravel sizes in the wetland. The inlet and outlet ends of the wetland bottom layer were constructed of coarse gravels in the range of 1.5–10 cm. Above this, a middle layer used smaller gravels of 1.5–4.0 cm. Finally, the surface layer, at 15 ± 3 cm depth in the filter bed, was filled with 1.0–1.5 cm pea gravel; Due to the evaporation of water, the constructed wetland only contained 240–260 m^3/d water on non-rainy days and the hydraulic retention time (HRT) was about 12 h. The high-productivity and easily-growing-in-gravel macrophytes *Scirpus tabernaemontani*, *Canna indica*, *Canna flaccida*, *Zizania latifolia*, *Juncus minimus*, *Pontederia cordata*, *Cyperus alternifolius*, and *Zantedeschia aethiopica* were cultivated in the constructed wetland. The proportion of each macrophyte was about 12.5% and the planting density was ~0.5 m × 0.5 m.

2.3. Plot experiment

A separate plot experiment, conducted in triplicate under controlled conditions, to check the effects of S and DCD in reducing N release. Six plots, each of 20 m^2 (4 m × 5 m), were cropped with leek. Each plot was isolated with PVC boards of 150 cm depth around the perimeter, with 135 cm underground to reduce the exchange of groundwater. The three control plots were fertilized with 480 kg urea/ha/yr urea. The three treatment plots were fertilized with 384 kg urea/ha/yr, 9.6 kg DCD/ha/yr and 86.4 kg S/ha/yr.

A drainage-collection device, designed by the Institute of Soil Science, Chinese Academy of Sciences (patent number: 200610037907.0) was used. The equipment for ammonia absorption was designed according to Wang et al. (2002). It was made of PVC with a 20-cm vent and a height of 40 cm. A double-layer sponge and glycerophosphate served as absorbents and KCl solution as the extractant.

2.4. Analyses and statistics

2.4.1. Plants and soil

The soil pH (water/soil = 2.5:1, v/v) was determined with a glass electrode. The NO_3^- in the soil was determined by UV-spectrophotometry after extraction with a 2 mol/L KCl solution (water/soil = 5:1, v/v). The NH_4^+ in the soil was determined by indophenol blue colorimetry at 625 nm. Total dissolved phosphorus (TDP) in soil was extracted by a 0.5 mol/L $NaHCO_3$ solution and determined by spectrophotometer at 700 nm (Ryan et al., 2001). Total phosphorus (TP) and total nitrogen (TN) in plants and soil were determined according to the methods of Rowland and Grimshaw (1985).

2.4.2. Water

Water sampling sites were C1 and C2 for ecological channels, from T1 to T6 for ecological trunk channel (Fig. 1). TN was measured by persulfate digestion and oxidation-double wavelength (220 nm and 275 nm) spectrophotometry. TP in water was measured colorimetrically by the persulfate digestion-molybdophosphate reaction (AHPA, 1995). Ammonia- and nitrate-N in water were determined by ion-selective electrode potentiometry with preliminary distillation (AHPA, 1995). The pH and dissolved oxygen (DO) were measured by DO, temperature and pH Systems (YSI incorporated, Model 95).

2.4.3. Sampling

The sediment samples (from T1 to T6) were collected evenly distributed in the ecological trunk channel (Fig. 1). Three replicates were collected per sampling site. The sediment was sieved and the material retained on the mesh (4.2 mm) was preserved in formalin (8%). In the laboratory, the sieve residue was sorted, with non-

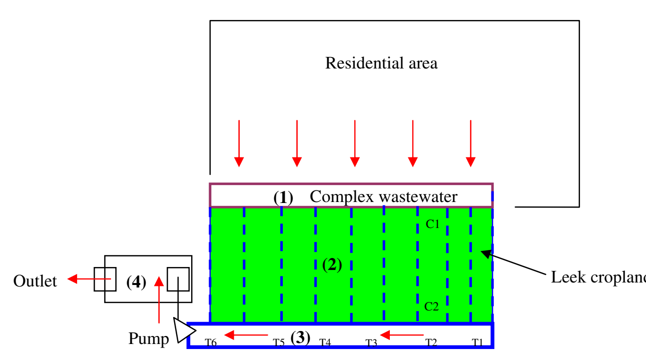

Fig. 1. The scheme of the eco-restoration system for nutrient removal from water and soil in the residential–cropland area. The water flow is from (1) to (4). (1) Deposit pool, (2) Ecological channels, (3) Ecological trunk channel and (4) Constructed wetland. The influent (complex wastewater) loads of the eco-restoration system are 500 m^3/d on non-rainy days (runoff < 10 mm).

Table 1
Annual average concentrations of complex wastewater including domestic sewage, farming effluent and livestock wastewater from residential area from April 2006 to March 2007 ($n = 12$).

pH	DO (mg L^{-1})	TN (mg L^{-1})	NO_3^-–N (mg L^{-1})	NH_3–N (mg L^{-1})	TP (mg L^{-1})	TDP (mg L^{-1})
7.92 ± 0.34	3.4 ± 1.3	54.52 ± 12.61	11.83 ± 4.22	37.91 ± 6.30	4.11 ± 2.65	1.03 ± 0.51

organic material and fragments of shells being discarded. Only the intact zoobenthos were identified and counted. Most of the benthic organisms were identified to the species level according to Guo's methods (1995). The macrophytic vegetation was also sampled in triplicate using transects. Details of the method are described in del Pozo et al. (2010). Simpson's diversity index (Simpson, 1949) was used to quantify the biodiversity of macrophytes and zoobenthos.

Due to the fluctuation of water amounts on rainy days (rainfall ≥ 10 mm/d) in the residential–cropland complex areas, the data considered in this study were only for dry days (rainfall < 10 mm/d). All samples were collected three days after rainy days (rainfall ≥ 10 mm/d) in order to reduce the impact of precipitation on the data.

The SPSS statistical software package (version 12.0) was used to analyze the data and the level of statistical significance was set at $P \leq 0.05$. The variation of the detected results was estimated by standard deviation and the differences among treatments were evaluated by analysis of variance (ANOVA).

3. Results

3.1. Ecological function improvement

The dominant alligator weed was removed after the eco-restoration system was initiated. It was calculated that 1.3×10^5 kg of alligator weed (wet weight) were removed, which resulted in 374.4 kg nitrogen and 27.2 kg phosphorus being removed from the study area. The biomass of the planted macrophytes (wet weight) harvested during the experimental period from August 2006 to July 2008 was 1.5×10^4 kg. This is equivalent to the removal of 19.8 kg nitrogen and 1.4 kg phosphorus.

The leek-dominated agricultural pattern in the cropland was changed after the eco-restoration system was instigated. The farming areas of corn, vegetable and fresh flowers increased from 0 to 13 000 m^2 between August 2006 and August 2008. Also, Simpson's diversity index for macrophytes in ditches and ridges markedly increased from 0.43 to 0.95. For the zoobenthos in the ecological trunk channel the index increased from 0.22 to 1.13. Four new zoobenthos, *Procladius choreus*, *Parakiefferella* sp., *Tanytarsus* sp., *Procladius* sp., were found at the end of the experiment.

3.2. Soil nutrient changes

The amount of fertilizer required was significantly reduced after the eco-restoration system was applied. The fertilizer in amounts of 128 kg N/ha and 28 kg P/ha per year was saved. Nutrient content of the cropland soil was evaluated on August 6, 2006 and August 6, 2008. The average concentrations of total nitrogen and phosphorus had decreased notably, from 3.49 to 3.05 g/kg and from 1.46 to 1.22 g/kg, respectively, as had the average TDP concentration in the soil (32.39–29.31 mg/kg), while the average concentration of nitrate in the soil had increased from 50.96 to 56.76 mg/kg (Table 2).

3.3. Aquatic nutrient removal

The properties of wastewater in the experimental area were investigated from April 2006 to March 2007 and summarized in Table 1. The results indicate that the wastewater suffered from nitrogen and phosphorus pollution. The TN concentration was dominant with major contributions from NO_3^-–N and NH_3–N. The wastewater was alkaline (pH 7.92 ± 0.34) and anoxic (DO 3.4 ± 1.3).

The removal efficiency of nutrients by the ecological channels is shown in Fig. 2a, b. The average removal efficiencies of TP and TN by the ecological channels on non-rainy days between April 2007 and July 2008 were 64% and 60%, respectively.

The average removal efficiency of TP from the ecological channels in summer (from April to July) had significantly increased from 42% in 2007 to 58% in 2008 ($P < 0.05$). On the contrary, the average removal efficiency of TN from the ecological channels had decreased from 58% to 50% between summer 2007 and summer 2008.

The removal efficiency of nutrients by the constructed wetland is shown in Fig. 2c, d. Overall, the average removal efficiencies from April 2007 to July 2008 were 49% for TP and 38% for TN. For summer 2007 and summer 2008, the average removal efficiencies of TP and TN increased significantly from 34% and 29% to 56% and 40% ($P < 0.05$), respectively.

Between April 2007 and August 2008, it was found that the TN and TP concentrations for water at the exit (T6) of the ecological trunk channel had decreased compared with that for the water at the entrance (T1) (Table 3). On the contrary the concentrations of TN and TP in the water did not decline along the flow of the ecological trunk channel (T2–T5) over the duration of the experiment. This indicates that there was nutrient release from the cropland soil.

Next, considering the release of nutrients from the cropland soil, the total efficiency of the eco-restoration system nutrient removal was assessed by determining the nutrient concentrations in the total inlet (the inlet of the deposit pool) and the total outlet (the outlet of the constructed wetland) of the complex wastewater. The results show that the overall average removal efficiency of TP and TN loads by the ecological ditch (including ecological channels and trunk channel) and the wetland were 83% and 88%, respectively. In addition, considering the nutrient release from the soil and the reduction of fertilizer use, the original outputs of 2.9 kg P/d and 29.7 kg N/d from the residential–cropland complex area were controlled by application of the eco-restoration system.

3.4. Decrease of nitrogen loss

Because the soil in cropland is alkaline (pH > 7.5) it easily leads to ammonia volatilization. Therefore, S and DCD were applied to the cropland to reduce the soil pH and thus decrease this nitrogen loss. The results showed that nitrogen concentrations in the leachate and side leakage were significantly decreased ($P < 0.05$) between the control and experimental plots (with the application of S and DCD). This indicated a decrease in dissolved nitrogen from

Table 2
Characteristics of soil fertility in cropland at the beginning and end of the experiment ($n = 16$).

	pH	Total nitrogen (g/kg)	Total phosphorus (g/kg)	Nitrate (mg/kg)	TDP (mg/kg)
Aug 6 2006	7.73 ± 0.18	3.49 ± 0.96	1.46 ± 0.38	50.96 ± 17.84	32.39 ± 20.42
Aug 6 2008	7.63 ± 0.21	3.05 ± 0.77	1.22 ± 0.23	56.79 ± 19.05	29.31 ± 17.32

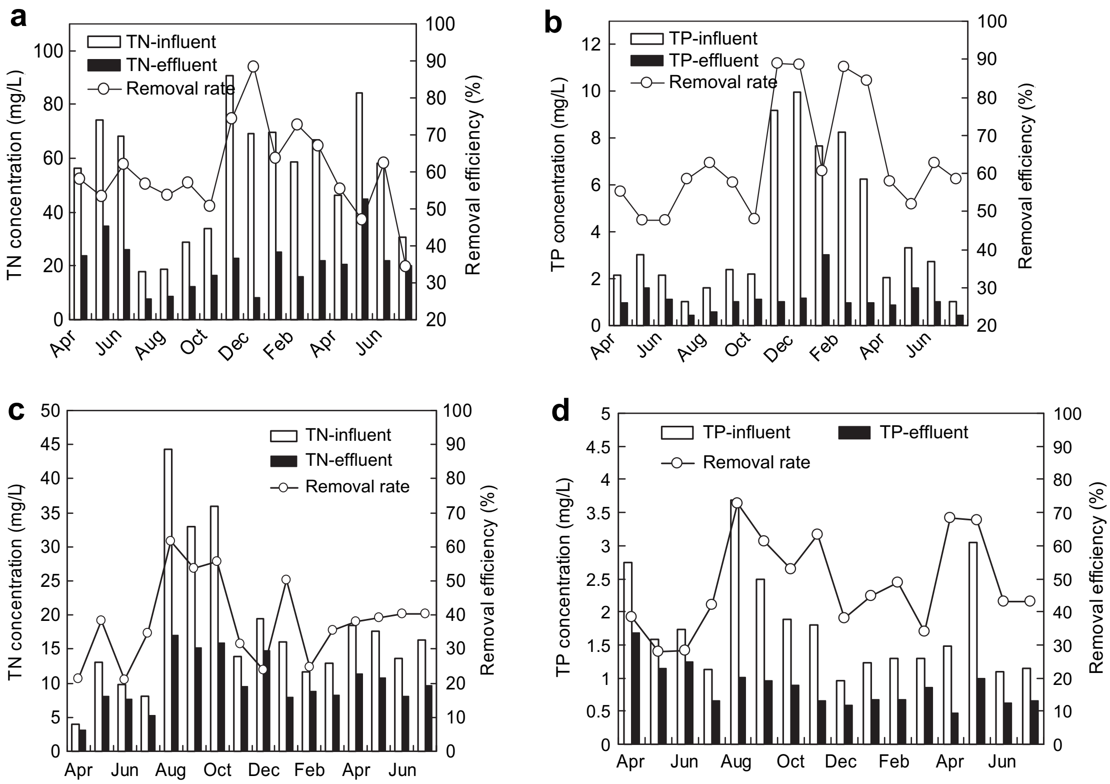

Fig. 2. The removal efficiency of the ecological channels (a and b) and constructed wetland (c and d) for treating TP, TN (on non-rainy days). The construction of the eco-restoration system was commenced in August 2006 and completed in December 2006. After this treatment ecosystem had been running continuously for three months, water samples from the ecological ditches and the constructed wetland were collected from April 2007.

the soil. Accordingly, the ammonia volatilization from the leek cropland was decreased significantly ($P < 0.05$) due to the treatment with S and DCD (Fig. 3).

4. Discussion

Before the eco-restoration system was implemented, the complex wastewater entered directly into the trunk channel and the cropland channels and induced the excessive growth of alligator weed (Fig. 4). When the system became operational, the alligator weed was removed. This led not only to decrease the nutrient loads from the cropland but also facilitate the farming, particularly relating to the use and management of water resources for irrigation, as well as increasing biodiversity and improving the health of food chains. As a result, these farming functions in the residential–cropland complex area were markedly enhanced. Indeed, the increase of Simpson's diversity indices for the macrophytes and zoobenthos demonstrated that the agricultural ecosystem health was improved and had achieved a steady-state condition.

Duckweed has an important potential for nutrient recovery from wastewater because of its rapid growth. The growth rate of duckweed biomass has a direct relationship with nutrient removal and recovery (Oron, 1994). In this study, duckweed was harvested three times a month, yielding $\sim 1.65 \times 10^3$ kg/ha (dry matter), which corresponds to the nutrient effects equivalent to ~ 151 kg urea and 93 kg calcium superphosphate originating from the fertilized cropland. The advantages of using duckweed are obvious: their high reproduction rate, ease of manual harvest from the water surface, high protein and low fiber contents. All these make duckweed cost-effective for recycling as a fertilizer.

The acidity produced (H^+) in the treatment of the soil with urea plus S and DCD was greater than that in the control (urea alone). From equation (1) it is evident (Le Châtelier's principle) that the reaction of OH^- with H^+ will favor more NH_4^+ thus reducing NH_3 volatility.

$$OH^- + NH_4^+ \rightleftarrows NH_3\uparrow + H_2O \tag{1}$$

It has been reported that soil is a good absorber of NH_4^+ (Smith et al., 2009). Thus, the concentration of NH_4^+ fixed in the soil treated with S and DCD was greater than in the control. According to the determination of the concentration of total nitrogen in water and soil samples, 80–90% was ammonia/ammonium ion. Accordingly, with the reduced soil pH of plots with applied S and DCD, ammonia volatilization decreased (Fig. 3).

In addition, the products of S oxidation and hydrolysis, via $S_2O_3^{2-}$ and $S_4O_6^{2-}$, can inhibit urea hydrolysis, which perhaps leads to

Table 3
The overall average concentrations of TP and TN at six sampling sites in the flow of the ecological trunk channel between April 2007 and August 2008 ($n = 25$).

Sample sites	T1 (entrance)	T2	T3	T4	T5	T6 (exit)
TN	24.56 ± 2.13	15.77 ± 2.27	17.05 ± 3.89	9.01 ± 2.01	18.49 ± 3.32	10.13 ± 1.31
TP	1.07 ± 0.21	1.12 ± 0.18	1.49 ± 0.22	0.45 ± 0.08	1.82 ± 0.42	0.92 ± 0.17

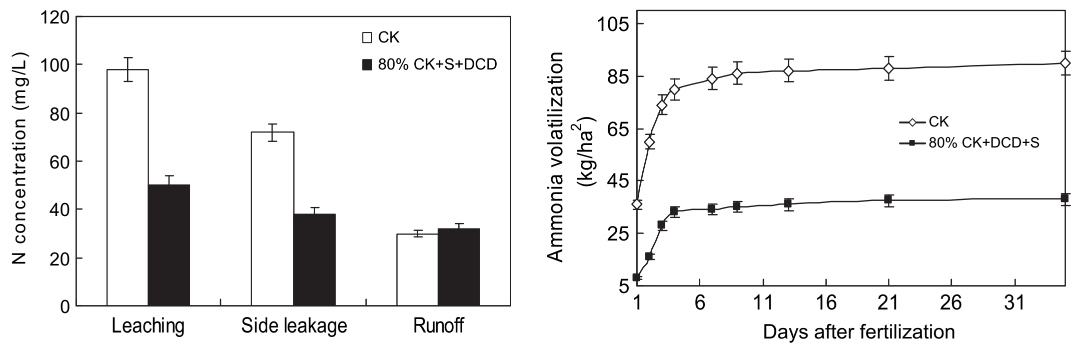

Fig. 3. The effects of the application of S and DCD on N concentrations in water and ammonia volatilization from the leek cropland.

further reduction of nitrate in the soil (Sullivan and Havlin, 1992). This in turn would explain why the amount of nitrogen leaching and side leakage from the S and DCD treated plots was less than that in the controls (Fig. 3).

Because the loss of nitrogen via volatilization, leaching and side leakage all declined, the utilization of N-fertilizer in the tillage layer was improved. Therefore, fertilizer management can be achieved without reducing production, which not only saves on the amount of chemical fertilizer input but also decreases the potential for agricultural non-point-source pollution from nutrients as well, due to the action of the soil as a complementary biofilter for pollutants (Oron, 1996).

The ecological ditch, as a rebuilt natural wetland, is an important approach for the reduction of non-point-source pollutants such as nutrient loads (Hajkowicz, 2009). The mechanism for the treatment of the ecological ditch was as follows. First, the ecological ditch had a large storage capacity and the primary runoff could be stored and further purified by multifunctional processes including adsorption by ceramsite, absorption by macrophytes and biodegradation by the microorganism assembly. Second, the substrate materials, which were used to infill the filtering ditches, adsorbed and filtered the pollutants from the runoff. Finally, the system had a long retention time, so it could provide favorable conditions for biological decomposition of small particles of organic matter. In this study, the macrophytes planted along the ditch walls and the absorbent ceramsite placed in the middle of the ecological trunk channel enabled the mechanisms mentioned above and facilitated the enhanced self-purification by the ecological ditch.

Furthermore, planting macrophytes elevated the DO and redox potential in the water by oxygen release from photosynthesis

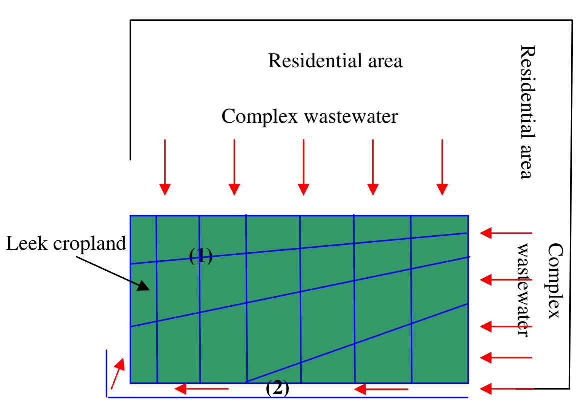

Fig. 4. Diagram of the residential–cropland area before initiating the eco-restoration system. (1) Channels in cropland and (2) Trunk channels. The complex wastewater was directly discharged into the channels in the croplands and trunk channel.

(Wiessner et al., 2002). In addition, the macrophytes assimilate many nutrients from the water and incorporated them into their biomass. Thus these nutrients were removed when the plants were harvested. In turn, the self-purification capacity of the ecological ditch was further enhanced.

The experimental area was situated in a subtropical zone at a high altitude (~1890 m) with strong radiant intensity (Zhang et al., 2002). In winter (from November to February), the evaporation of water is greater than in other months due to the plateau weather (KMABDL, 2004). The macrophytes were harvested each year in March. Coverage of the ecological channel was very dense during winter, which decreased the evaporation. Thus, the removal efficiencies of nutrients in cold months were much higher than in hot months (summer) with the same pollution loads.

Subsurface wetlands have been proven to be a powerful technology which can successfully remove a broad range of contaminants found in municipal wastewater (García et al., 2005; Huertas et al., 2006). Our study showed that the constructed wetland effectively purified the complex wastewater. The overall removal efficiency of TP and TN were close to the mean removal efficiencies as reported by Börner (1992).

Large fluctuations were observed in the removal efficiencies of TN in different months. Much lower removal efficiency of TN occurred in the cold season (Fig. 2). Nitrification is a temperature-dependent process, which is significantly reduced when the temperature is below 10 °C (Werker et al., 2002; Verstraete and Philips, 1998). Also, the gaseous nitrogen produced via volatilization and denitrification is dependent mainly on temperature and ventilation. Furthermore, plant growth is definitely a seasonal process. The lowered efficiency of TN removal in constructed wetlands in winter may result from the lower temperature (Maltais-Landry et al., 2009). A similar result occurred with the removal rate of TP; it was also negatively affected by the low temperature (Fig. 2).

5. Conclusion

This eco-restoration system has been implemented on a pilot scale for 2 years and found to be effective and cost-efficient. The system is simple in terms of building, operation and maintenance, and therefore suitable for rural and low technology communities. Results have shown that the restoration of the agricultural ecosystem was amongst the important drivers to reduce nutrient discharge from a complex residential–cropland area. Also, the use of this system was found to facilitate farming in ways such as improving the drainage and irrigation. It is a promising and environmentally benign technology because the in situ removal of nutrients from soil and water in residential–cropland complex areas decreases the downstream surface-water eutrophication risk.

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