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Assessing nutrient losses of reclaimed wastewater irrigation in paddy fields for sustainable agriculture

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ABSTRACT

An experimental field study was performed during the growing season to assess water and nutrient balances in a paddy field over a 3-year period. The plots were separated according to irrigation water: groundwater (TR#1), wastewater (TR#2), and filtered wastewater with ultraviolet (UV) treatment (TR#3). The hydrology and water quality of rainfall, irrigation, surface water, and infiltration were monitored throughout the crop stages. More than half of the total water inflow of about 1840 mm in each treatment was contributed by precipitation and the remainder by irrigation. The water balance analysis indicated that approximately 13% of the total outflow was lost by surface drainage, 30% was consumed by plant uptake, and 57% was lost by evapotranspiration and infiltration. The nitrogen (N) levels in the irrigation water in the mass inputs for TR#1 and TR#3 were 22% and 49%, respectively, while the output balances in the drainage water for TR#1 and TR#3 averaged 2% and 6%, respectively. The N in the crop harvest for TR#1 and TR#3 occupied 59.62 and 121.35 kg ha^{-1}, respectively. The N in the fertilizer comprised a large proportion of the N in TR#1 while the N in the irrigation water and fertilizer were the major inputs in TR#3. The major P input was fertilizer in TR#3, and crop harvest was a main output in the P balance. In contrast, surface drainage and infiltration were relatively small components, due to the high drainage outlet height. The difference between inputs and crop harvest shows that it is possible to improve water quality by reducing the fertilization rates in paddy fields irrigated with reclaimed wastewater.

1. Introduction

Extensive lowland areas in Asia and other parts of the world are under rice paddy cultivation (Odhiambo and Murty, 1996). In the Republic of Korea, paddy fields cover an area of 11,500 km^2, which comprises 61% of the nation's total cultivated area (Kim et al., 2009). Korea suffers from a limited water supply, including agricultural irrigation water, due to population growth, urbanization, and economic development (Jang et al., 2008). A recent national survey on the future Korean water supply and demand reported that the country can expect a shortage of over 0.44 billion m^3 of water by 2030 (MLTM, 2006).

Because paddy rice production requires large volumes of water, agricultural irrigation is allocated upwards of 47% of the total annual water use in Korea. A paddy field is blocked by a levee to maintain a ponded water condition and the water level is dependent on the outlet height. The irrigation amount is determined from the optimal ponding water depth (Kim et al., 2008) and a total of about 1250 mm of water is generally required per rice paddy during the growing season, which is primarily supplied by irrigation.

Reclaimed wastewater can be an alternative water resource for supplementary irrigation in areas that suffer from water shortages or unsatisfactory water quality since agricultural irrigation water does not usually require the same high grade of water quality as drinking water (Kang et al., 2007; Jang et al., 2010b). Guidelines for reclaimed wastewater irrigation have been adopted for paddy fields in Korea (MOE, 2005). As a result, more data are available to help clarify potential human health problems and assess the environmental effects associated with reclaimed wastewater irrigation of paddy fields. However, few reports of practical wastewater reuse for rice paddies have appeared (Kang et al., 2007; Jang et al., 2008, 2010b). In contrast, wastewater reuse for upland crop irrigation is being practiced in many countries (Cooper, 1991; Asano and Levine,

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1996; Al-Lahham et al., 2003; Kiziloglu et al., 2007; Brunetti et al., 2007; Palese et al., 2009).

Rice paddy culture requires large amounts of water and nutrients for producing staple foods. At present, farming in Korea uses high inputs of fertilizers (Harris, 1998), substantial amounts of which can be lost through surface drainage unless there is a careful balance between the input and the amount that rice plants actually use (Yoon et al., 2006). In addition, water quality in Korea suffered seriously during the rapid industrialization of the late 1980s, but, due to ongoing restoration efforts, has since improved (Yoon et al., 2003). However, the water quality of many streams and lakes often does not meet established standards, and periodic algal blooms in most reservoirs indicate that further efforts to safeguard quality are needed (Yoon et al., 2003). Furthermore, the possibility that water quality will deteriorate as reclaimed wastewater is used to irrigate paddy fields is a matter of concern. Therefore, it is necessary to determine the nutrient losses that result from surface drainage from paddy fields. Recently, studies have examined this question in Korea, with varying results (Han et al., 1999; Cho and Choi, 2001; Cho and Han, 2002; Cho, 2003; Cho et al., 2003; Yoon et al., 2003, 2006). However, few studies have examined practical wastewater reuse or high-nutrient-concentration irrigation of paddy fields.

The objectives of the current study are to investigate water and nutrient balances in paddy fields irrigated by groundwater, wastewater, and reclaimed wastewater and to assess nutrient losses with different agricultural management practices in paddy fields irrigated with water from a typical stream or agricultural reservoir and reclaimed wastewater.

2. Materials and methods

2.1. Experiment site and design

The experimental plots are in the Byoung-Gem (BG) paddy field (E 37°12′32″, N 127°01′18″) located near the Suwon wastewater treatment plant in Gyeonggi-do, Korea. The present study was conducted for three crop-years from 25 May, 2006 to 21 October, 2008. A randomized complete block design with split plot arrangements was used with three treatments and four replicates on 5 m × 5 m plots (Fig. 1). The three treatments were separated according to the irrigation water: groundwater (TR#1), untreated wastewater (TR#2), and filtered wastewater with ultraviolet (UV) treatment (TR#3). A small scale wastewater reclamation system with a LCHE-WRT filter system (Maeng et al., 2006), UV treatment unit, and pipelines supply irrigation water from the wastewater effluents. A groundwater well was installed to supply water for TR#1. There was one rain gauge, three infiltrometers, and three five-set ceramic porous cups at three plots. The flume was designed with a V-notch weir with the water gauge and the V-notch was positioned above 15 cm from the base in order to maintain a constant outlet height, with water levels controlled to be 1–10 cm according to rice growth stage (Kim et al., 2008). Three weirs were initialized to the same level for measuring the water depth at each treatment.

Average annual rainfall and evaporation in the study area are 1259 and 1091 mm, respectively. The average annual temperature in this area is 11.6 °C. The annual mean temperature during the irrigation periods range from 16.7 to 25.2 °C. The soil in the experimental field is Gangseo series (coarse loamy, mixed, nonacid, mesic family of *Aquic Fluvaquentic Eutrudepts*) (NIAST, 2000).

For this experiment, 1-month-old rice seedlings (*Oryza sativa cv. Chucheongbyeo*) were transplanted in May and harvested in October during 2006–2008. Fertilizers are typically applied three times, during the pre-plant, tilling, and panicle growing stages, but for this experiment they were applied one time during the pre-plant (N:P:K = 55:45:40 kg ha^{-1}) based on high-nutrient-concentration irrigation. Insecticides were sprayed in June of every year to exterminate rice water weevils, and weeds were controlled manually.

2.2. Measurements and analysis methods

Ponded water depth in each experimental plot was continuously measured by an automatic float type water level recorder. Inflow was measured using a water gauge at the inlet pipe, and outflow was measured using weirs installed at the outlet of three plots. The samples of irrigation and ponded water were collected on a weekly or biweekly basis. Three sets of the double ring infiltrometer were installed on each plot to measure daily water loss by deep percolation. Percolation water quality was sampled by five ceramic porous cups embedded at a depth of 100 cm below the soil surface. Rainfall was recorded using a tipping bucket rain gauge at the site, and evapotranspiration was estimated by the Penman–Monteith equation (Allen et al., 1998). Rainfall water was sampled when storms occurred. Water samples were analyzed by the standard methods of APHA (1995) for conventional parameters including total nitrogen (T-N) and total phosphorus (T-P) concentrations.

Soil samples were collected from experimental plots before transplanting and after harvesting. After clearing organic matter from the surface, three soil sub-samples were taken from the root zone (2–30 cm below the soil surface) of each plot. The soil samples were analyzed for physical and chemical properties with the American Society of Agronomy (ASA) and Soil Science Society of America (SSSA) methods for soil analysis (Chapman and Pratt, 1961). The collected soil samples were analyzed for pH, concentrations of T-N and T-P, and the main cations. The control plot in the Gi-cheon paddy fields, which is near a suburb of Suwon, was located approximately 6 km northeast of the BG paddy field. These plots were irrigated with water from the Gi-cheon reservoir, which satisfies the current agricultural water quality criteria of Korea. An extensive hydrologic and water quality monitoring system was established there in 1996 (Kim et al., 2008).

Rice plant samples of root and grain were collected at each plot after harvesting, and these were analyzed for T-N and T-P concentrations using the micro-Kjeldahl method (Jackson, 1967). Mass loads of T-N and T-P were calculated by multiplying water volume and corresponding concentration.

Water balance in the paddy fields is estimated by the variation in ponded water depth (WD), expressed as

$$\mathrm{WD}_i = \mathrm{WD}_{i-1} + \mathrm{IR}_i + \mathrm{PR}_i - (\mathrm{DR}_i + \mathrm{ET}_i + \mathrm{IN}_i) + \mathrm{Un}_i \tag{1}$$

where, WD is ponded water depth, IR is the amount of irrigation water, PR is the amount of precipitation, DR is the amount of surface drainage through a weir, ET is the amount of evapotranspiration, IN is the amount of infiltration water, and Un is the unmeasured amount. The subscript i represents the ith day.

The nutrient input to the paddy fields is categorized as either natural supply or fertilization, where natural supply includes atmospheric deposition and irrigation water, and fertilization includes mineral and organic sources (Yoon et al., 2003). Nutrient output includes surface drainage through the weir, deep percolation, and plant uptake. The general mass balance equation for both T-N and T-P is approximated in this study as

$$I_{\mathrm{IR}} + I_{\mathrm{PR}} + I_{\mathrm{FR}} = O_{\mathrm{DR}} + O_{\mathrm{IN}} + O_{\mathrm{HR}} \tag{2}$$

where, I_{IR} is input from irrigation, I_{PR} is input from rainfall, I_{FR} is input from fertilization, O_{DR} is output by surface drainage, O_{IN} is output by deep percolation, and O_{HR} is output by crop harvest. The nutrient balance in a paddy field is also affected by other factors, including acidic deposition, biological N fixation, mineralization, immobilization of soil N and P, ammonia volatilization,