Irrig Sci
DOI 10.1007/s00271 011 0292 2

ORIGINAL PAPER

Short-term soil nutrient impact in a real-time drain field soil moisture–controlled SDI wastewater disposal system

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Received: 18 February 2011 / Accepted: 1 June 2011

Abstract The Alabama Black Belt area is widespread of Vertisols that are generally unsuitable for conventional septic systems; nonetheless, systems of this type have been widely used in this region for decades. In order to explore alternatives for these conventional septic systems, a real-time soil moisture controlled subsurface drip irrigation wastewater disposal system was integrated and field tested in a Houston Vertisol for 1 year. This automated disposal system effectively limited wastewater disposal during unfavorably wet drain field conditions. However, the resulting nutrient supply into the drain field was observed to be in surplus to crop growth requirements. Soil cores taken at the conclusion of the 1-year study indicated evidence of nitrate and phosphorus leaching. Available nitrates in the top 100 cm of soil showed a decreasing trend but were higher than all other parallel controls. Soil crop-available phosphorous in the soil increased below the drip line, as result that may be ascribed to soil cracking that was not properly controlled at the test site. Despite the demonstrated deficiencies, integrating timing of wastewater disposal with soil moisture conditions can supplement existing municipal or decentralized community wastewater treatment disposal systems.

Communicated by S. O. Shaughnessy.

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Introduction

Natural wastewater treatment systems are generally considered cost-effective in comparison with centralized sewer collection and treatment (Kruzic 1997; Reed et al. 1995). Soil-based conventional septic systems are widely used for individual homes and small communities where public sewer service is not anticipated in the near future (USEPA 2002). In a conventional septic system, wastewater from households normally stays in septic tanks for 24 48 h and then is disposed into drain fields without considering the actual drain field conditions at the moment of wastewater disposal (Alabama State Department of Health 2006). Numerous field surveys have indicated the inadequacy of prevailing design criteria for drain field sizing (Charles et al. 2005; Moelants et al. 2008; Nam et al. 2009), mainly due to underestimated septic tank effluent strengths (Charles et al. 2005) and/or wastewater hydraulic dosing controls that ignore seasonally changing drain field conditions (USEPA 2002). Furthermore, due to conventional septic systems' complete reliance on soil properties for contaminant attenuation (Oron 1996), soils having too high or too low percolation rates are generally considered not suitable for these type of systems (Spicer 2002; USEPA 2002).

According to the USEPA (2002), approximately 44% of the houses in Alabama are served by conventional septic systems with an average system malfunction rate of 20%. Within the state of Alabama is the centrally located Alabama Black Belt region, an area of 14,000 km^2 and a population of 394,000, which has been using conventional septic systems for decades, despite the fact that 52% of the soils in this region are Vertisols (Geographical Survey of Alabama 1993). Vertisols are expansive clay soils that not only form deep cracks in drier seasons or years (Amidu and Dunbar 2007; Kishne et al. 2009) but also swell closing soil pores during wet weather conditions (Bouma and Loveday 1987; Weaver et al. 2005). Such soil physical behaviors make these Vertisols inherently unsuitable for conventional septic systems (Alabama State Department of Health 2006). However, conventional septic systems are widely used in the Alabama Black Belt region accompanied with a prevailing aging system (He et al., in press), and there are numerous public health incidences caused by conventional septic system failures in this region that have drawn national attention to these system deficiencies in the Alabama Black Belt (Alabama State Department of Health 2006; McCoy et al. 2004).

With an intent to explore alternatives for those unsuitable conventional septic systems, a real-time drain field soil moisture controlled subsurface drip irrigation (SDI) wastewater disposal system was designed and installed as a field trial in a Houston clay soil in this region. The field experiment was carried out from June 2007 to June 2008, a period of historic normal rainfall. The SDI was adopted to exploit its potential to provide a uniform hydraulic distribution in the drain field (Ruskin 1992) and restrict nutrient movement within a confined soil wetting front (Jnad et al. 2001). The concept of drain field soil moisture controlled hydraulic dosing was adopted from agriculture applications. Phene and Howell (1984) first used a custom-made soil matric potential sensor to control SDI for water savings. As electronic technology advanced, Phene et al. (1992) achieved real-time control over irrigation through automated field water balance estimation. Nowadays, scheduling irrigation timing based on field conditions are gaining more practical application with proven water savings and reductions in nutrient percolation (Meron et al. 1996; Muñoz-Carpena et al. 2003; Dukes and Scholberg 2005; Duan and Fedler 2009; Duan et al. 2010).

This paper presents the drain field soil nutrient (nitrogen, N and phosphorus, P) impact after this 1-year field study and assesses the engineering feasibility of this tested wastewater hydraulic dosing strategy. The evaluation was carried out using monthly soil water nutrient levels, seasonal field crop nutrient uptakes, and soil core nutrient profiles.

Materials and methods

Site description

The field study was conducted on a leveled Houston clay soil (Very-Fine, Smectitic, Thermic Oxyaquic Hapluderts) site at the Alabama Black Belt Research and Extension Center in Marion Junction, Alabama. The site has increasing clay content with depth up to 71% at 152 cm. Field capacity (1/3 bar, SSSA 2002) at the site occurs between 0.37 and 0.45 $m^3\ m^{-3}$ with a site uniformity of 96.9%, and measured soil saturated hydraulic conductivity (K_{sat}) of the experimental site ranges between 0.12 and 0.29 $\mu m\ s^{-1}$ with a site uniformity of 76.2% (Soil Conservation Service 1970).

Field experiment design

The experimental SDI system (treatment I) was sized for a plot that was designed for a single family home of three persons and was studied in parallel with three other different control subplots (treatments II IV, Fig. 1). Treatment I consisted of 30 drip tubes (Geoflow, CA) of 27.4 m long installed at approximately 20 25 cm deep. The drip tube lateral distance and the emitter spacing were 61 cm. The drip emitters were pressure compensating, and their overall hydraulic uniformity performance was laboratory tested and classified as average (data not shown) according to ASAE EP 405.1 (ASAE 2003).

To observe the impact of wastewater application on soil water nutrient levels, treatment II was designed as the same size SDI system as treatment I, but received only clean well water that contained negligible nutrient concentrations. Treatments I and II shared the same SDI dosing pump (76 lpm) that turned on/off based on the readings of two capacitance type volumetric soil moisture sensors (Delta-T, UK) buried at the 20 cm and 45 cm depths between these two treatments (Fig. 1). The two soil moisture sensors were precalibrated using soils from the experimental site (data not shown), and the soil moisture ($m^3\ m^{-3}$) thresholds used for SDI dosing pump on/off control were set at 0.40 (on) and 0.45 (off) with the intent to avoid hydraulic loading of treatments I and II beyond field capacity. Once the soil moisture system was operational, the SDI dosing pump was initiated for a 5-min period after every 55 min.

Due to the difficulty of obtaining consistent supply of septic tank effluents on the experimental site, the applied wastewater was artificially prepared by spiking clean well water with a nutrient solution to approximately 80 mg total N L^{-1} in the form of urea ($(NH_2)_2CO$), 10 mg total P L^{-1} in the form of orthophosphate, 100 mg TOC (total organic carbon) L^{-1}, and negligible solids. Well water was used because underground water is the major water source for the

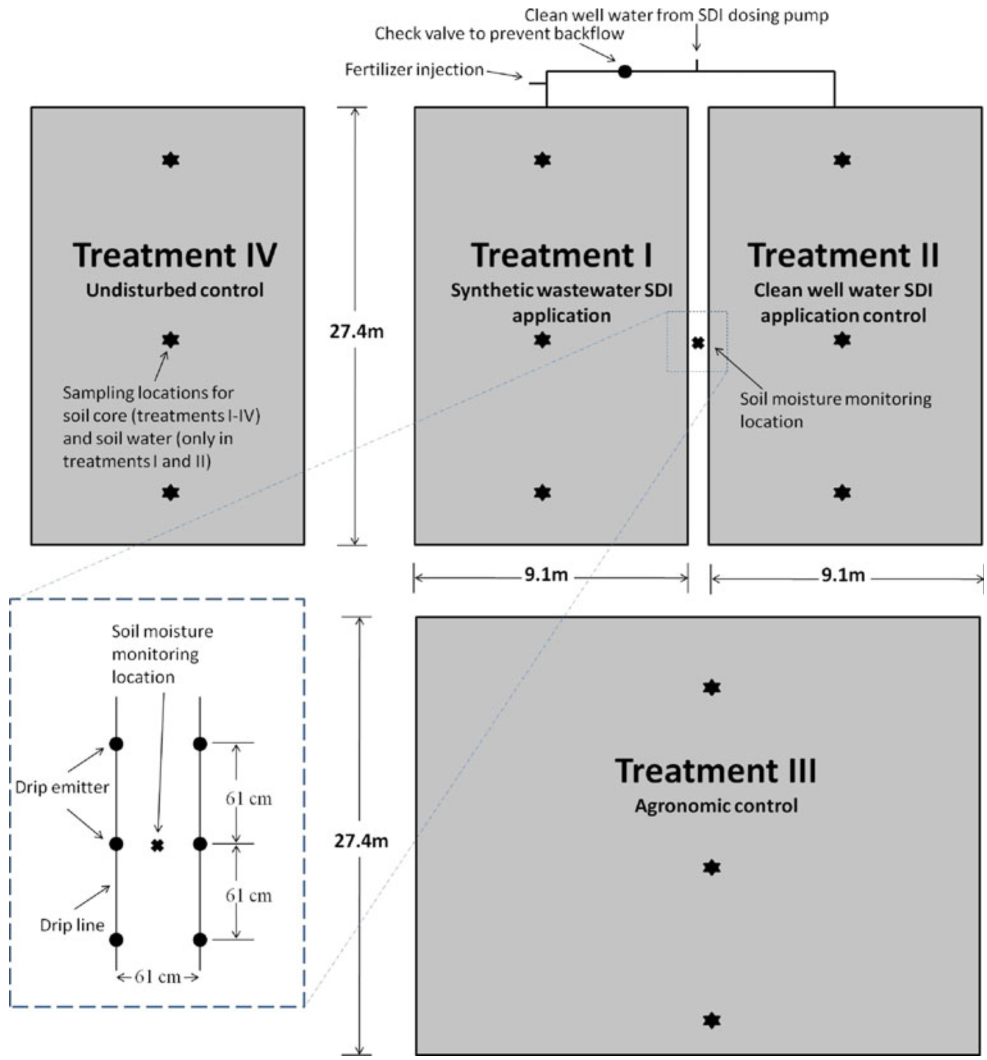

Fig. 1 Field layout of the experiment (treatments I and II each has 30 drip lines with a lateral distance of 61 cm; the distance between treatments I and II is also 61 cm)

Alabama Black Belt region (Geographical Survey of Alabama 1993), so that its pH and chemical makeup were assumed to be similar to household wastewater in this region. The simulated nutrient strength was based on reports that typical septic effluents contain 40 80 mg N L^{-1} with 75% in NH_4-N and 25% in organic N and 3 20 mg P L^{-1} with 85% in orthophosphate (Venhuizen 1995). The chemical analysis of this artificially prepared wastewater is listed in Table 1.

A local crop rotation recommended by Auburn Agricultural Extension was performed in treatments I and II: two seasons of sorghum-sudangrass (*Sorghum bicolor L.*) from June to November, a winter wheat (*Triticum aestivum L.*) and a rye (*Secale cereale L.*) mix from November to the following June. Sorghum-sudangrass was planted at 33.6 kg seed ha^{-1} on a 18-cm row spacing. Winter wheat was planted at 67.2 kg ha^{-1} on 18 cm rows, and rye was broadcast at 22.4 kg ha^{-1}.

To compare crop nutrient uptake efficiencies, treatment III was designed as an agronomic control having the same crop rotation as treatments I and II, but without irrigation. However, fertilizer was applied to treatment III at the beginning of each crop-growing season at 67 kg N ha^{-1}. In order to monitor background soil conditions, a barren field was left undisturbed during the entire study as a background control (treatment IV).

Table 1 The chemical analysis of the artificially prepared wastewater

pH	EC (dS m^{-1})	TKN (mg L^{-1})	TP (mg L^{-1})	K (mg L^{-1})	Ca (mg L^{-1})	Na (mg L^{-1})	Mg (mg L^{-1})
8.1 (7.6 8.5)	0.1 (0 0.2)	80 (65 100)	10 (7.4. 13)	12.0 (10.8 14.7)	6.3 (5.5 7.7)	53.7 (42.9 61.4)	1.0 (0.9 1.3)

Reported values are the means and the ranges of the measurements (in parenthesis) during the course of the field experiment

Field sampling

Monthly soil water was sampled by suction lysimeters (Irrometer, CA) at the depths of 15, 30, and 46 cm at three locations in treatments I and II (Fig. 1). After filtration through a 0.22-μm membrane, filtrates were analyzed for NH_4-N and NO_3-N by colorimetric analysis (Sims et al. 1995) and total P by ICAP (Thermo Jarrel Ash 9000). At the end of each season, field crops were harvested for dry matter yields and plant tissue nutrient contents (HCl digestion method, Hue and Evans 1986). One year after the wastewater application, 100-cm-long soil cores were collected using a tractor-mounted Giddings® hydraulic probe at three locations in each treatment (Fig. 1). Each soil core was subsequently divided by depth into five subsamples: 0 20, 20 40, 40 60, 60 80, and 80 100 cm. Subsamples were dried in a forced-air oven at 60°C for 4 days, pulverized, and screened to pass a 2-mm sieve. Soil total N was quantified by combustion using a LECO® CHN-600 analyzer. Soil total P was quantified using the perchloric acid procedure per Shelton and Harper (1941). Crop-available P was determined using the Mississippi extract method (Lancaster 1970). Soil pH was measured using 1:1 soil/water (wt/vol) slurries with a pH meter (Orion, US). Soil crop-available N was determined by extracting soil subsamples with 1 mol L^{-1} KCl solution and analyzing the extract for NH_4-N and NO_3-N (Sims et al. 1995).

Results and discussion

Wastewater hydraulic dosing pattern

As indicated from the fluctuating soil moisture readings shown in Fig. 2, the system prevented wastewater dosing during wet weather field conditions by withholding wastewater until the field moisture content dropped to the predetermined "operational" window of 0.40 0.45 m^3 m^{-3}. Relatively higher hydraulic dosing rates and frequencies were observed from late spring to late autumn (average 0.41 cm $days^{-1}$), whereas during the winter months, the system showed consistent near zero dosing due to naturally saturated field conditions. Since the strength of the synthetic wastewater was relatively consistent throughout the study, the resulting nutrient loadings in treatment I should have followed the wastewater hydraulic dosing pattern with subsequently higher loadings during the warm season than during the cold season.

Crop nutrient uptake

Compared with treatment III (conventional agronomic practice), treatment I (drain field) received a substantially higher supply of N than treatment III in all three crop-growing seasons (Table 2, 3.98 5.18 times higher during the warm season and 2.78 times higher during the cold season). The higher N supply resulted in a comparably higher crop yield for the 1st cutting of sorghum-sudangrass (3.65 times higher than treatment III). However, crop-available N uptake efficiencies in treatment I were lower than treatment III for all three crop-growing seasons (Table 2). Phosphorous loadings to treatment I were also substantially higher than crop uptake (Table 2), except for the winter wheat and rye season when there was essentially zero P loading into the drain field from wastewater disposal (Fig. 2). However, with no P fertilizer, treatment III presented similar crop yields as treatment I for the 2nd cutting of sorghum-sudangrass and the winter wheat and rye. These observations suggest there was a substantial nutrient surplus from wastewater application in treatment I.

Soil water nutrient

Compared with treatment II (soil irrigated with clean well water only with no fertilizer, data not shown), soil water nutrient levels in treatment I (drain field) were enhanced by the wastewater application (Fig. 3). However, no seasonal pattern emerged to match the observed wastewater hydraulic dosing pattern. These observations indicate nutrient leaching beyond the 46 cm depth in treatment I consistently occurred due to wastewater application.

Comparing all measurements at the three sampling depths, the average NO_3-N and total P in soil water showed a decreasing trend with depth (Fig. 3a, c), while the average NH_4-N showed an increasing trend with depth (Fig. 3b). Since NO_3-N was not originally in the applied wastewater, its presence might be explained by the consistent urea lysis (fertilizer dissolution) and nitrification of applied NH4-N. The formed NO3-N may have been consistently lost to soil nitrogen cycles (denitrification, plant uptake, etc.) as described by Brevé et al. 1997) during its downward movement. The decreasing trend of total P in soil water can be explained by the P immobilization mechanisms with downward movement (Sawhney and Hill 1975; Venhuizen 1995; Sparks 2002).

Soil nutrient profile

An accumulative result of one year of wastewater application was that total N in the soil depth profiles (Fig. 4a) and crop-available NH4-N (Fig. 4b) in treatment I (drain field) indicated gradually decreasing trends at similar depths to other treatments.

However, based on the depth profile of NH_4-N in soil water (Fig. 4b), an increasing trend of crop-available NH_4-N should be expected. This discrepancy might be explained

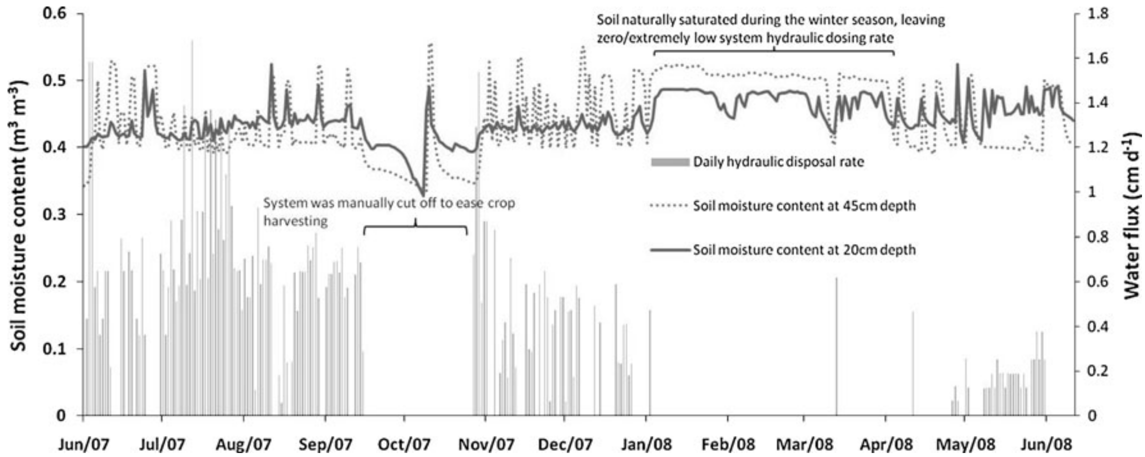

Fig. 2 Daily system hydraulic dosing rate (cm/days) and soil moisture readings ($m^3\ m^{-3}$) at the 20 and 45 cm depths in the drain field of treatments I and II

Table 2 Crop yield, nutrient application, and crop uptake of treatments I and III during the field study

Growing crops	Dry mass yield ($kg\ ha^{-1}$)		Total N applied ($kg\ ha^{-1}$)		Total N uptake ($kg\ ha^{-1}$, % of total N applied)		Total P applied ($kg\ ha^{-1}$)		Total P uptake ($kg\ ha^{-1}$, % of total P applied)	
	Trt I	Trt III	Trt I	Trt III	Trt I	Trt III	Trt I	Trt III	Trt I	Trt III
Sorghum sudangrass 1st cut (Jun 07 Aug 07)	5,910	1,620	267	67	103 (38%)	28 (42%)	52	0	11 (21%)	4
Sorghum sudangrass 2nd cut (Aug 07 Nov 07)	820	774	347	67	14 (4%)	10 (15%)	31	0	2 (6%)	1.7
Winter wheat and rye (Nov 07 Jun 08)	13,200	11,700	186	67	138 (74%)	136 (203%)[1]	11	0	17 (154%)[1]	14
Annual (Jun 07 Jun 08)	19,900	14,000	800	201	255 (32%)	174 (86%)	94	0	30 (32%)	19.7

[1] Crop uptake of N or P was greater than fertilized, meaning soil provided additional N or P to meet crop growing requirements

by a quick loss of applied NH_4-N to the soil nitrogen cycle (Brevé et al. 1997). It should also be noticed that the measured soil pH levels fluctuated around 8 (Fig. 4d), which are favorable for NH_3 volatilization (Sigunga et al. 2002), NH_4^+ fixation within smectitic clay sheets (Allison et al. 1953; Liu et al. 2008). The possible scenario is that NH_4-N percolated through soil horizons and was consistently lost to NH_3 volatilization, NH_4^+ fixation, and denitrification, thus leaving no signs of NH_4-N leaching in the soil cores.

NO_3-N is easily leached out of soils due to its high mobility (Sparks 2002). When NO_3-N leaching occurs, an increased soil crop-available NO_3-N along the pathway of NO_3-N plumes is generally anticipated (Sánchez Pérez et al. 2003). Such a pattern was shown by the plant-available NO_3-N in treatment I, which was higher than the other treatments. The soil crop-available NO_3-N in treatment I also showed a decreasing trend with depth that corresponds to the results of soil water samples (Fig. 3c), suggesting a consistent NO_3-N loss to soil nitrogen cycles (denitrification, plant uptake, etc.) over the soil profile (Brevé et al. 1997). Nevertheless, it appears that NO_3-N leaching was imminent beyond the 100 cm depth if the wastewater application had been continued.

The wastewater contributed approximately 800 kg N ha^{-1} $year^{-1}$ to treatment I, representing approximately 12% of the soil total N (6,783 kg N ha^{-1}). From a mass balance point of view, only approximately 32% of the applied N was accounted for by crop uptake, leaving the remaining 68% N as field accumulated or lost. Soil core analysis suggests that NO_3-N leaching and NH_3 volatilization were the most likely fates for the remaining 68% of N. However, further deep soil profile information would be needed to confirm this speculation.

Soil total P levels in treatment I showed a decreasing trend over a 100-cm soil depth, similar to the other three treatments (Fig. 4e). However, soil crop-available P (Fig. 4f) in treatment I showed an elevated trend below

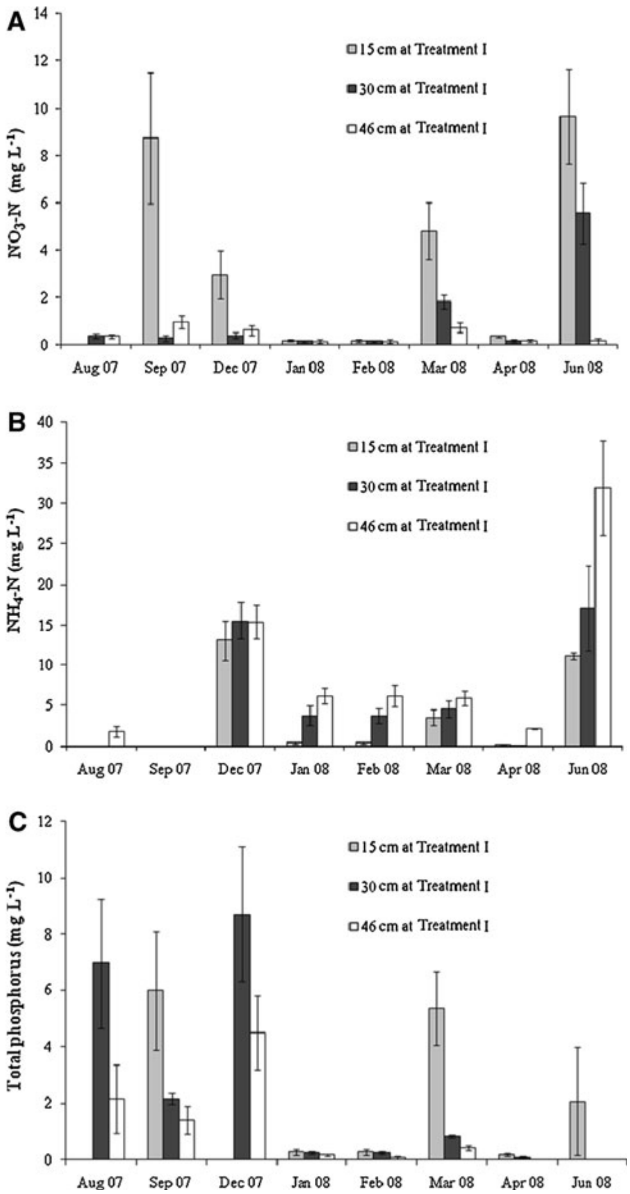

Fig. 3 Monthly soil water nutrient levels at the 3 sampling depths in treatment I

30 cm depth, indicating the likelihood of P leaching. This observation is contrary to some general concepts that P movement is negligible in soils due to numerous P immobilization mechanisms, such as chemical precipitation and chemical/physical adsorption (Sawhney and Hill 1975; Venhuizen 1995; Sparks 2002). However, at this experimental site, physical soil cracking developed to a depth of around 50 cm during the summer, which is normal for Vertisols (Amidu and Dunbar 2007). Furthermore, more than 100-cm-deep cracks have been reported in similar Houston clays (Kishne et al. 2009). Even though the experimental site was characterized as having a high uniformity of field capacity and K_{sat}, the wetting pattern under the SDI system may not have extended widely enough to prevent soil cracking development during the summer time. Therefore, wastewater could have been carried into deeper soils without proper soil treatment as a result of soil cracking.

Wastewater contributed approximately 94 kg P ha^{-1} year^{-1} to treatment I, representing approximately 4.7% of the soil total P (2,000 kg P ha^{-1}). From a mass balance point of view, only approximately 32% of the applied P was accounted for by crop uptake. Consequently, soil total P accumulation seems inevitable in the long run if P deep percolation can be effectively controlled.

Indicated system deficiencies

Although more conclusive results could be obtained from extended studies, the observations from this short-term experiment have already indicated deficiencies of the tested wastewater hydraulic dosing strategy that need to be corrected in order to promote a more effective control over soil nutrient movement. One concern is that the nutrient supply into the drain field was not coupled with crop uptake, on both the timing and quantity. This result could increase nutrient leaching potential and threat underground water systems (USEPA 2002). Charles et al. (2005) advocated to estimate a higher septic nutrient level (250 mg total N L^{-1} and 36 mg total P L^{-1}) for sizing drain fields for conventional septic systems. As for this study, tuning down the wastewater nutrient strength seemed necessary for the sustainability of this tested wastewater hydraulic dosing strategy. Furthermore, SDI wastewater disposal is normally mandated in the use secondary effluent (treated wastewater) (Alabama State Department of Health 2006). Therefore, the results of this study also indicated the tested wastewater hydraulic dosing strategy, at its current form, is not suitable as a stand-alone method to handle raw septic effluents.

Another concern raised by this short-term field study is that clay soil cracking might have not been effectively curtailed in the drain field, despite the wastewater hydraulic dosing on/off set points were around the measured field capacities. This could be partially ascribed to the 0.61-m spacing between emitters and drip lines, which might not be optimum for the tested water dosing strategy. Numerous studies, especially through numeric modeling, have indicated the necessity to adjust emitter spacing according to each specific SDI dosing strategy so as to minimize dry areas between emitters by providing adequate soil wetting zones between emitters (Schwartzman and Zur 1986; Zur 1996; Kandelous and Šimůnek 2010). One correction to the experimental system can be reducing emitter and drip line spacing to within the range of the expected wetting fronts for each emitter in the soil so as to potentially enhance water

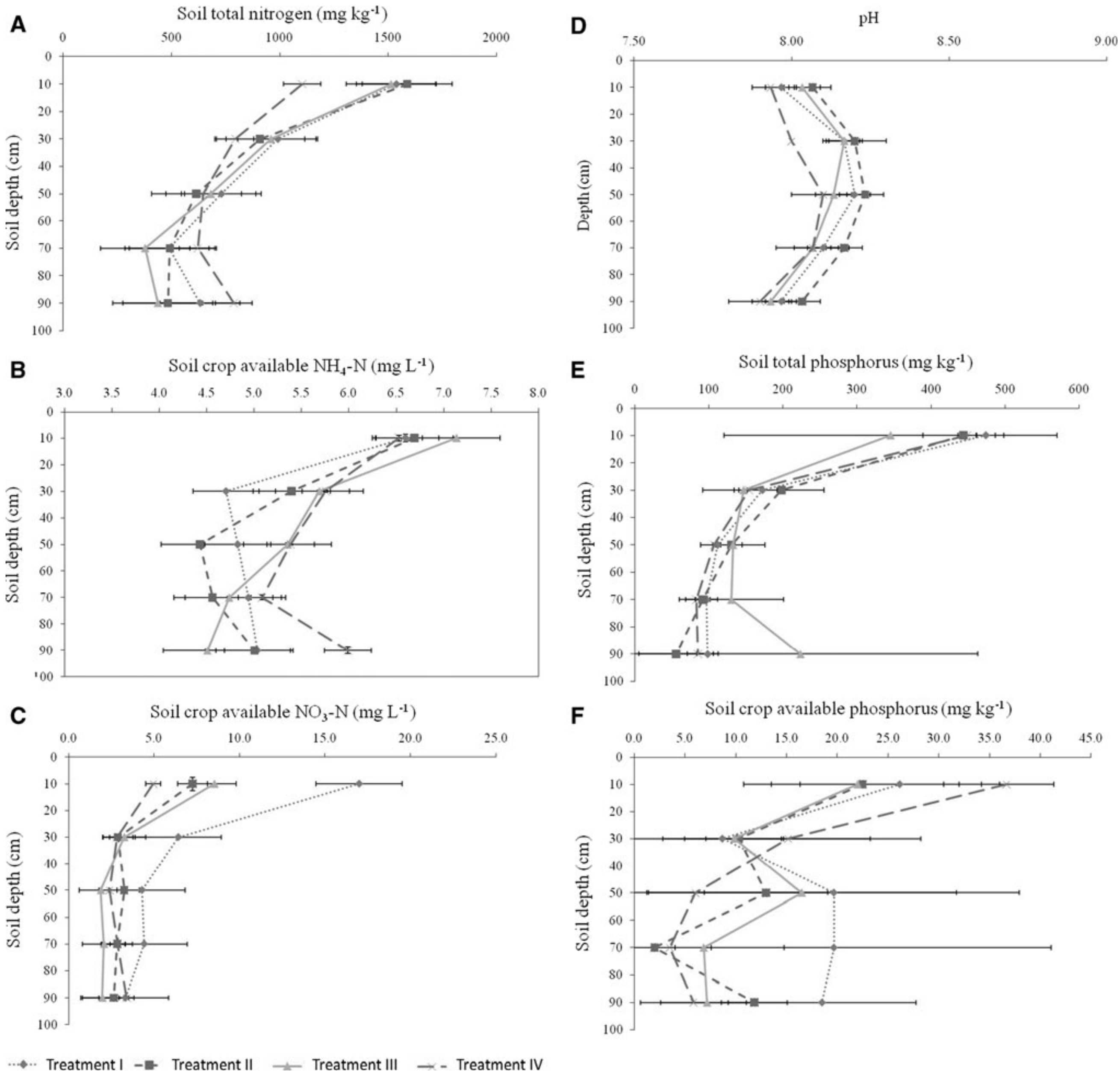

Fig. 4 Soil core nutrient analysis results of the four field treatments 1 year after the wastewater application started (each data point represents the average of 3 measurements, and *error bars* represent standard deviations)

distribution and limit soil cracking. Also, putting soil moisture sensors closer to the emitters might increase the chances for the soil moisture sensors to capture the wetting front before it reaches soil cracks, thus calling off water dosing that might contribute to water percolation loss. Adjusting the wastewater hydraulic dosing on/off set points might also help on clay soil cracking control in this study. Nevertheless, these suggested remedies still need field tests for final verifications.

Despite these indicated deficiencies, the experimental system as designed and installed still showed its potential in preventing wastewater disposal during unfavorable drain field conditions. With proper modifications to improve its performance in drain field nutrient movement control, this tested wastewater hydraulic dosing strategy can supplement existing municipal or decentralized community wastewater treatment facilities. Nevertheless, due to the limitation of this short-term field experiment, an extended field study is recommended but not limited to: observe nutrient horizontal movement in the drain field and study potential impact from other ingredients normally contained in wastewater such as heavy metal, pathogens, pharmaceutical substances. Furthermore, adequate replication of field treatment and increased field sampling locations and frequency should also be implemented.

Conclusions

A real-time drain field soil moisture controlled SDI wastewater disposal system was tested in a Houston clay soil during normal rainfall conditions from June 2007 to June 2008. The study assessed the environmental sustainability of the wastewater dosing strategy by analyzing soil nutrient impacts.

The nutrient loading into the drain field was higher during the warm season than during the cool season. The resulting nutrient supply was found in surplus to the crop-growing requirement during all crop-growing seasons. This nutrient surplus suggests a potential for groundwater pollution, which was supported by the enhanced soil water NH_4-N, NO_3-N, and total P levels in the top 46 cm of soil. However, there were no signs of soil total N and P accumulation or crop-available NH_4-N leaching in the top 100 cm. Some soil crop-available NO_3-N and P leaching was observed, which suggests that the wastewater dosing strategy in its current form is not suitable as a stand-alone method for disposal of septic tank effluent in Houston clay soils.

The leaching of soil crop-available P was attributed to clay soil cracking, which is a challenge for the proposed wastewater disposal strategy in this region. Possible remedies include reducing emitter and drip line spacing to enhance water distribution and limit soil cracking, putting soil moisture sensors closer to emitters to increase sensitivity to the wetting front, and adjusting the wastewater hydraulic dosing on/off set points might also help on soil cracking control. Extended field studies with more field replications under a variety of weather conditions are recommended to test these remedies for more definitive results on the applicability of SDI wastewater disposal based on real-time drain field soil moisture levels.

The experimental system successfully prevented wastewater disposal during unfavorable drain field conditions by withholding wastewater until the field moisture content dropped to the predetermined "operational" window. Therefore, despite the deficiencies identified during limited field testing, the wastewater hydraulic dosing strategy with proper modification may yet find an application as a supplement to existing municipal or decentralized community wastewater treatment facilities.

Acknowledgments This research was funded by Alabama Agricultural Land Grant Alliance (AALGA) and Alabama Water Resources Research Institute (AWRRI). National Soil Dynamics Laboratory of Agricultural Research Service in United States Department of Agriculture also partially aided in soil sampling analysis. The authors wish to thank James Holliman at the Alabama Black Belt Research and Extension Center for his dedicated field support. The Departments of Biosystems Engineering, Agronomy and Soils, and Civil Engineering at Auburn University also provided the convenience for this research.

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