Evaluation of Leachfield Aeration Technology for Improvement of Water Quality and Hydraulic Functions in Onsite Wastewater Treatment Systems

A Final Report Submitted to

The NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET)

Submitted by

Jose A. Amador, George W. Loomis, David Kalen, Erika L. Patenaude, Josef H. Gorres
Dept. of Natural Resources Science
University of Rhode Island
Kingston, RI 02881

And

David A. Potts
Geomatrix, LLC
Killingworth, CT

September 2, 2007

CICEET

This project was funded by a grant from NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology, NOAA Grant Number(s) NA04NOS4190109

UNIVERSITY *of* NEW HAMPSHIRE

Expanded Executive Summary and Key Findings

This project addressed the problems associated with pollution of coastal resources from failing septic systems in Narragansett Bay. In some areas of Narragansett Bay as much as three-quarters of the total N load may be attributable to wastewater sources, with OWTS estimated to contribute 51% of the N inputs into Greenwich Bay. Elevated N inputs within the Narragansett Bay watershed were identified as an important contributor to a large-scale fish kill observed in Greenwich Bay in August 2003. Improvement of septic system management is among the recommendations of a report by the RI Dept. of Environmental Management on the causes and solutions to the water quality problems in Greenwich Bay.

We tested SoilAir, a relatively inexpensive, non-invasive, innovative technology for its ability to improve the hydraulic and water quality functions of septic system leachfields at the pilot and field scales. The technology involves intermittent aeration of the leachfield, which promotes oxidation of excess organic material at the infiltrative surface and supports conditions for removal of N, P, organic C, and fecal coliform bacteria. As such, intermittent leachfield aeration can improve hydraulic function and lower contaminant inputs into surface, ground and coastal water resources.

SoilAir offers a number of advantages over existing tools. It is a simple system, essentially involving a blower, electronic controls for blower operation, and a means to deliver air to the leachfield. As such, it is relatively quick and easy to install, and requires minimal disturbance of the leachfield area. It is retrofitted on existing hydraulically-failed conventional systems, and thus does not involve new construction. SoilAir is also less expensive than available alternatives and requires little interaction of the homeowner with the technology, making long-term adoption by homeowners more likely.

In contrast, the main alternative for repair of a failing conventional leachfield is often construction of a new soil absorption area in a different part of the property. On many small properties an alternate area is not available because of limited space, requiring excavation and removal of the failed drainfield, which has high costs associated with disposal of contaminated soil and other drainfield materials. Even where space is available, this is option is considerably more expensive (an estimated $8,000, not including removal of failed system) and disruptive than installation of a SoilAir system, requiring the use of heavy machinery for excavation and site restoration, and can take over a week to complete. In addition, a replacement leachfield does not provide the improvement in water quality and does not eliminate the long-term potential for repeated hydraulic failure. Alternative technologies offer improved water quality and diminished potential for hydraulic failure, but can present problems similar to those for construction of a new leachfield, particularly high expense ($18,000 - $30,000) and disruption of property during installation.

The patented SoilAir technology has been used for restoration of hydraulically-failed septic system leachfields in 12 states in the U.S. and Canada, with approximately 300 systems installed since 1996. The ability of intermittent aeration technology to improve the water quality function of conventional OWTS has been tested extensively at the pilot scale, with improvements observed in removal of N, P, BOD, and fecal coliform bacteria. Performance has also been evaluated in terms of effects of soil depth, hydraulic load, antibiotic inputs, and temporary loss of aeration. Field evaluation of water quality functions has also been carried out for over a year at group homes with failed conventional septic systems in Washington County, RI.

Regulations governing adoption of all alternative OWTS technologies, including SoilAir, vary considerably among states, and can vary among local and regional regulatory agencies within a state. As such, one of the main barriers to widespread adoption faced by SoilAir may be the tangle of regulations at different levels of government.

The end user groups for intermittent aeration are likely to be designers and installers of innovative OWTS, many of which have become aware of the technology through workshops and other outreach efforts put forth by the New England Onsite Wastewater Training Program University of Rhode Island as part of this project.

Key Findings

- **Cost.** Equipment costs for a "typical" residential SoilAir application ranges from $1,800 to $5,000, depending on system requirements. Installation costs are site-specific, but tend to be around $2,500. System installation can often be accomplished in one day. In general, equipment and installation costs for SoilAir technology are at least three to five times lower than alternative technologies such as advanced treatment systems and biotreatment trenches. Operating costs are limited to energy to power the blower, with a typical system drawing approximately 280 Watts. When used for nitrogen removal, based on our test sites, the blower typically runs for 4 hours per day. Based on the national average cost for electric power of 10.16¢/kiloWatt-hour, the cost to run a blower is 2.85¢/hour, or 11.4 ¢ per day. Many other technologies need to run air constantly through treatment units to maintain performance, resulting in higher operating costs (as much as 250 Watts/h for 24 h, equivalent to 60.96¢ per day).
- **Maintenance requirements.** Operation and maintenance (O&M) visits to residential sites are made twice a year; less frequently if the system is equipped with a modem and remote telemetry. O&M costs are about $300 per year. The only component requiring routine maintenance is the air filter. The SoilAir system has the advantage that, if it breaks down, the leachfield can carry out its water absorption function for a period of time. Performance appears less variable than other nitrogen removal technologies.
- **Speed.** The infiltrative capacity of existing hydraulically-failed systems can be restored within a few days of installation, with improvements in nitrogen removal likely to be observed after a few weeks. In new systems, nitrogen removal capacity may develop more quickly.
- **Ease of use.** Ease of use from the homeowner’s perspective should be similar to that for a passive, conventional soil absorption system, which requires little interaction with the system, just periodic inspection and pumping of the septic tank.
- **End user capacity requirements.** Similar to other technologies. Requirements for installation and running of SoilAir technology are comparable to other technologies.

Abstract

Failing or improperly functioning OWTS constitute public health and environmental hazards because of their potential to degrade ground, surface, and coastal water quality. In some areas of Narragansett Bay as much as three-quarters of the total N load may be attributable to wastewater sources, with OWTS estimated to contribute 51% of the N inputs into Greenwich Bay. Elevated N inputs within the Narragansett Bay watershed were identified as an important contributor to a large-scale fish kill observed in Greenwich Bay in August 2003. Improvement of septic system management is among the recommendations of a report by the RI Dept. of Environmental Management on the causes and solutions to the water quality problems in Greenwich Bay. We tested SoilAir, a relatively inexpensive, non-invasive, innovative technology for its ability to improve the hydraulic and water quality functions of septic system leachfields at the pilot and field scales. The technology involves intermittent aeration of the leachfield. Our goal was to **evaluate the effectiveness of SoilAir in restoring leachfield hydraulic function and improving water quality at the pilot and field scales.** Pilot-scale studies employed soil-filled mesocosms representing leachfield soil and dosed with domestic septic tank effluent under controlled conditions. These were used to assess the effects of introduction of intermittent aeration, short-term (48 h) loss of aeration (LOA), and increased hydraulic load (IHL) (from 12 to 24 cm d^{-1} for 24 h) on hydraulic function, quality of water, and removal of N, P, BOD_5 and fecal coliform bacteria. Intermittent aeration of unaerated mesocosms resulted in improved STE infiltration as well as increased levels of dissolved O_2 and NO_3, lower concentrations of NH_4 and Fe(II), and more acidic pH in drainage water. Removal of total N increased from < 10% to > 50%. Removal of BOD_5 increased from <90% to 99% under intermittent aeration, with more modest increases in total P and fecal coliform removal in response to the treatment. Immediate effects of LOA included lower levels of DO and lower pH, and lower removal of total N, total P, BOD_5 and fecal coliforms. However, these values returned to pre-disturbance levels 1 to 12 days after aeration was restored. IHL resulted in lower levels of DO and NO_3 and lower pH, but these values returned to pre-disturbance levels within 4 to 29 days. Removal rates for total N increased from 50 to 75% in response to IHL, returning to pre-disturbance levels after 32 days. Removal of BOD_5 and fecal coliforms decreased significantly in response to IHL, returning to pre-disturbance levels within 4 days. Field evaluation of intermittent aeration technology on hydraulic function and water quality was conducted on hydraulically-failed conventional wastewater treatment systems at 6 group homes managed by the RI Dept. of Mental Health, Retardation and Hospitals, all within Washington County, RI. Evaluation was conducted over a period of 13 months, with Phase I (pre-installation) comprising the first 6 months of the study, and Phase II (operation) the remaining 7 months. Removal rates for total N, total P, and total organic carbon generally remained the same or increased during the operational phase (II) relative to the pre-installation phase (I) despite marked reductions in the amount of infiltrative surface necessary for optimization of the technology. Although field conditions introduced considerable variability relative to the controlled conditions of the laboratory tests, results from laboratory evaluation of SoilAir technology are supported by field evaluation data. Together, the results of our study suggest that SoilAir may be a viable,

low-impact, inexpensive alternative technology to reduce nutrient contamination of surface, ground and coastal waters by failed and functioning OWTS.

Introduction

Approximately ¼ of the population of the U.S. relies on onsite wastewater treatment systems (OWTS) for disposal and renovation of domestic wastewater, a number that has remained constant for the past 30 years (U.S. Census Bureau, 2002). Failing or improperly functioning OWTS constitute public health and environmental hazards because of their potential to degrade ground, surface, and coastal water quality. Of special concern are elevated inputs of N, biodegradable organic C, and pathogens, which can impact adversely the utilization of ground and surface water bodies as a result of eutrophication and increased human health risks (U.S. EPA, 2002). Elevated N inputs within the Narragansett Bay watershed were identified as an important contributor to the large-scale fish kill observed in Greenwich Bay in August 2003 (RIDEM, 2003). In some areas of Narragansett Bay as much as three-quarters of the total N load may be attributable to wastewater sources (Wigand et al., 2001). OWTS are estimated to contribute 51% of the N inputs into Greenwich Bay (Gomez and Urish, 1998). Among the recommendations of a report on the causes and solutions to the water quality problems in Greenwich Bay is improvement of septic system management (RIDEM, 2003).

Conventional septic system technology is sensitive to fluctuations in volume and strength of wastewater, and is prone to hydraulic failure in the absence of proper maintenance. Improvements in the quality of water as it passes through the leachfield are often minimal, especially for N (Kaplan, 1987; U.S. EPA, 2002). New technologies developed to improve the quality of effluent from OWTS can be expensive ($16,000 to $35,000 per system), making them difficult to adopt by most homeowners. Alternatives, such as leachfield replacement, may be as expensive as new OWTS technologies, and may only postpone hydraulic failure.

We tested a new, relatively inexpensive, non-invasive technology to improve the hydraulic and water quality functions of leachfields at the pilot and field scales. The technology, SoilAir, involves intermittent aeration of leachfields and has been shown to enhance infiltration of septic tank effluent (STE) and was expected to enhance the quality of water draining from leachfield soil. Over 300 field tests (commercial and household) of this technology by Geomatrix, LLC (of which co-PI David Potts is president) in the U.S. and Canada have shown that the aeration technology can rejuvenate septic systems by restoring hydraulic function in a matter of days. In a previous study Potts et al. (2004) evaluated the effects of intermittent aeration on removal of total N, biochemical oxygen demand (BOD_5) and fecal coliform bacteria from STE in sand-filled leachfield mesocosms relative to unaerated mesocosms. The results of the pilot study indicated that intermittent aeration enhances removal of total N, fecal coliform bacteria, and BOD_5, with the effects of aeration on water quality being dependent on loading rate (Potts et al, 2004).

Continuous aeration to improve leachfield hydraulic function has been evaluated by others. For example, Converse et al. (1994) documented the successful use of sand filters and aerobic treatment units to hydraulically reclaim failed septic drainfields. However, they did not report on the quality of drainage water beneath the reclaimed drainfields. Other current technologies for improving water quality from septic systems include those aimed specifically at removing nitrogen (e.g. recirculating sand filters, textile filter units, fixed activated sludge systems) or BOD and pathogens (e.g. single-pass sand filters, UV/ozonation units) (U.S. EPA, 2002). While effective, these technologies share a number of drawbacks: (i) they tend to be expensive, which can be a significant barrier to adoption by homeowners, (ii) they involve installation of additional treatment unit(s) at an added cost to the homeowner, and require additional space; (iii) installation involves major, albeit temporary, physical disruption of the homeowner's yard; and (iv) the risk of off-site transport of sediment from the disturbed site during the construction and post-construction phases is increased considerably. By contrast, installation of a SoilAir system is minimally invasive, poses less risk of off-site movement of sediment, and is relatively less expensive. These features may increase the likelihood of adoption by homeowners and state and local regulatory agencies, and thus to lower inputs of N, microbial pathogens, and BOD into Narragansett Bay. It is, to the best of our knowledge, the only patented technology of its kind available (Potts, 2000).

We conducted an evaluation of the effects of intermittent aeration technology on water quality and hydraulic function in onsite wastewater treatment systems at the pilot scale and at field sites within the Narragansett Bay watershed.

Objectives

Our main goal was to **evaluate the effectiveness of intermittent aeration technology in restoring leachfield hydraulic function and improving water quality.** This goal was addressed at two scales:

1. **Pilot scale.** We evaluated the effects of SoilAir technology during initiation of intermittent aeration and its response to fluctuations in STE load and temporary loss of aeration under controlled conditions.
2. **Field scale.** SoilAir technology was tested *in situ* in three conventional OWTS and compared to three conventional systems without the technology in Washington County, RI.

Methods

Pilot Scale Experiments

Study site. Pilot-scale experiments were conducted at a research facility in Westbrook, CT, USA adjacent to a two-family home fitted with a conventional septic system. The home was inhabited continuously by 3 to 6 people during the study. STE was diverted to an air-tight storage tank (1,325 L capacity; residence time ~2 d) situated in a climate-controlled (17-19ºC) room above the laboratory and mixed at regular intervals using a pump. Every 6 h effluent from the storage tank was pumped to dosing tanks in the laboratory (Fig. 1), which were also climate-controlled (18-20ºC). The wastewater dose flowed by gravity into a series of stainless steel cylindrical lysimeters (35.6 cm i.d., 61.0 cm height). The bottom of the lysimeters was filled with 7.5 cm of No. 4 synthetic silica sand (dia. = 0.71 to 0.21 mm, uniformity coefficient < 1.8). A total of

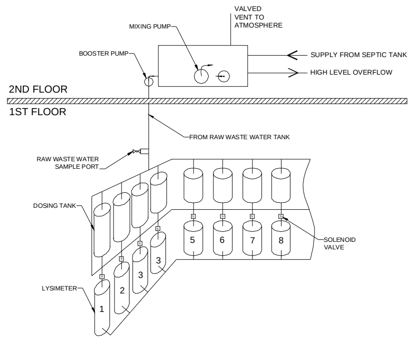

Fig. 1. Schematic of pilot-scale laboratory facility in Westbrook, CT (drawing not to scale).

30 cm of soil, a mixture of B and C horizon soil (sandy-skeletal, mixed, mesic, Typic Udorthent; 92% sand, 8% silt; pH of 7.6) from Kingston, RI was placed over the sand. This soil is typical of that used in leachfield construction in Rhode Island. The remaining space in the mesocosms (~22 cm) constituted the headspace. The mesocosms began receiving wastewater on 13 August, 2003 at a rate of 4 cm d^{-1}. On 22 June, 2004, this rate was increased to 12 cm d^{-1}.

The headspace of mesocosms was either vented to the leachfield trench of the adjacent house to simulate a conventional leachfield atmosphere (LEACH treatment) or was supplied with air at regular intervals to maintain an O_2 level of ~0.21 mol mol^{-1} (AIR treatment) using a blower. Each treatment was replicated 4 times.

Experiment 1 – Effect of changes in headspace gas composition. On December 15, 2004 LEACH mesocosms were switched from a headspace atmosphere consisting of leachfield gases to an ambient air atmosphere. This treatment is referred as L→A. In addition, the headspace of AIR mesocosms was switched to vent to a leachfield. This treatment is referred to as A→L. Data on water quality, headspace gas composition, and removal efficiencies in the two treatments were collected for 492 days prior to the start of experiment and after the switch.

Experiment 2 – Effects of loss of aeration. Temporary loss of aeration (LOA) was achieved by turning off the air blowers to the AIR mesocosms for 48 h. All other conditions remained as described for Experiment 1. Data on water quality, headspace gas composition, and removal efficiencies were collected prior to and after the LOA event.

Experiment 3 – Effects of increased hydraulic load. To evaluate the effects of increased hydraulic load (IHL) on AIR mesocosms, the frequency of dosing was increased from 3 cm every 6 h (12 cm d^{-1}) to 3 cm every 3 h (24 cm d^{-1}) for 24 h. All other conditions remained as described for Experiment 1. Data on water quality, headspace gas composition, and removal efficiencies were collected prior to and after the IHL event.

Field Scale Evaluation

Study Sites. Field evaluations of the performance of SoilAir technology were carried out at six OWTS in Washington County, RI. The sites were instrumented in February 2006. All were group homes managed by the RI Dept. of Mental Health, Rehabilitation and Hospitals (RI MHRH) in Washington County, RI, with three sites in Charlestown, two in South Kingstown, and one in Exeter (Table 1). Five of the six systems rely on leachfield trenches for septic tank effluent dispersion, with galleys employed in the remaining system.

Each septic tank was fitted with a sampling pipe placed near the tank outlet 45 - 60 cm below the effluent level. The sites were instrumented with three clusters of

Table 1. Location, soil series, means of STE disposal, and site instrumentation for field sites used in the study.

				Site Instrumentation								
				C1[a]			C2			C3		
Site No.	**Town**	**Soil Series**	**Type of drainfield**	**W[b]**	**30**	**90**	**W**	**30**	**90**	**W**	**30**	**90**
1	South Kingstown	Canton-Urban complex	Trench	Y	Y	Y	Y	Y	Y	Y	Y	Y
2	South Kingstown	Sutton	Trench	N	N	N	Y	Y	Y	Y	Y	Y
3	Charlestown	Merrimac	Trench	N	Y	Y	N	Y	Y	N	Y	Y
4	Charlestown	Canton-Charlton complex	Trench	Y	Y	Y	Y	Y	Y	Y	Y	Y
5	Charlestown	Hinckley-Enfield complex	Trench	Y	Y	Y	Y	Y	Y	Y	Y	Y
6	Exeter	Hinckley-Enfield complex	Galley	Y	Y	Y	N	Y	Y	Y	Y	Y

[a]C1 = upgradient; C2 = between trenches/galleys; C3 = downgradient. See text for a detailed description.
[b]W = groundwater well; 30 = lysimeter 30 cm below infiltrative surface; 90 = lysimeter 90 cm below infiltrative surface. See text for a detailed description.

ceramic cup lysimeters and/or slotted wells. Cluster locations within a site were as follows:

- Cluster 1 (C1): Upgradient from leachfield
- Cluster 2 (C2): Between leachfield trenches or galleys
- Cluster 3 (C3): Downgradient from leachfield, immediately adjacent (15 - 20 cm) to outer wall of last trench or galley

Within each cluster, sampling devices were installed as follows:

- Lysimeters: Bottom of cup at a depth of 30 and 90 cm below infiltrative surface (designated C1-30, C1-90, C2-30, C2-90, C3-30, C3-90).
- Wells: Slotted (15-30 cm) section partially or completely below groundwater level at time of installation (designated C1-W, C2-W, C3-W).

Three of the six sites (Sites 1, 4 and 5) had the full complement of instrumentation (Table 1). Site restrictions prevented installation of C1 at Site 2, of groundwater wells at Site 3, and of the C2 groundwater well at Site 6.

Installation of SoilAir systems. SoilAir™ system components, time dosing pumps and associated controls were retrofitted onto Sites 1, 3 and 4 (Fig. 2). In conjunction with this work, approximately 50%, 50% and 68% of the leachfield system capacity was isolated from the wastewater flow at Sites 1, 3 and 4, respectively, in order to further test the hydraulic capabilities of the SoilAir technology (Fig. 2). Just prior to installation of the SoilAir and septic tank effluent pump (STEP) components, the septic tanks were pumped.

A B C D

Fig. 2. (A) Air blower, filter and controller components of the SoilAir system; (B) Septic tank effluent flow to a portion of the leachfield trenches was blocked at the distribution box to test hydraulic performance; (C) Septic tank effluent pump (STEP) system; (D) Sealing concrete structures prior to installation of SoilAir system.

At each site a STEP system was installed in the second compartment of the most downstream septic tank (Fig. 2). Float switches were set to drop the effluent levels in the tank by approximately 6” (15 cm) to provide for flow equalization capacity. Air lines, consisting of 2” (5 cm) Schedule 40 PVC, were run from the SoilAir enclosure and connected to the pipe between the septic tank and the leaching system. Distribution boxes (D-boxes) and inspection ports were sealed to prevent the short-circuiting of air (Fig. 2). Temporary power and control cables were connected to the SoilAir system, STEP system and associated float switches. A telecommunications cable was connected between the SoilAir controls and the building to facilitate modem communication for remote telemetry of the systems.

The microprocessor-based controllers were configured to operate both the SoilAir blower and the timed-dose STEP system. The STEP system was programmed to run for a set period of time, which correlated to the desired dose. The STEP dose interval was programmed to run every six hours, unless a high level or low level float switch was triggered. In addition to controlling dosing, this allowed us to quantify the hydraulic load to the leachfield. The SoilAir blower was programmed to remain inactive for approximately one hour after a wastewater dose. After this delay interval, the SoilAir blower was programmed to run for a set period of time, and turn off for a period of time. The blower and STEP system were interlocked to prevent simultaneous operation, with priority given to the STEP system.

Sampling. Groundwater wells were pumped 24 h prior to sampling using a peristaltic pump. In instances when the well could not be pumped to dryness, the volume of water pumped was at least 5 times the standing volume. A hand pump was used to apply a vacuum (~ 80 kPa) to the cup lysimeters 24 h prior to sampling.

Samples of water from wells and cup lysimeters, as well as septic tank effluent samples, were collected using a peristaltic pump fitted with silicon tubing. Water samples were placed in autoclaved polyethylene screw-cap bottles and stored in a cooler filled with ice packs immediately after collection. Samples of soil gases were drawn from the wells after water was sampled.

Calculation of constituent removal rates and fluxes. The mean concentration of N, P, chloride and TOC in samples from C1 (upgradient or background) cup lysimeters was subtracted from mean concentrations for samples from C2 and C3 lysimeters (within and down gradient of the leachfield, respectively) at the same depth to correct for background effects. The apparent reduction, R, for constituent X was calculated using the equation:

$$R_X = 100 \times [(C_{X\text{-}STE} - C_{X\text{-}LYS})/C_{X\text{-}STE}] \qquad \text{[Eq. 1]}$$

where $C_{X\text{-}STE}$ is the concentration of constituent X in septic tank effluent and $C_{X\text{-}LYS}$ is the background-corrected concentration of X in a sample from a lysimeter, both expressed in mg L^{-1}. The flux, Φ, of a constituent X (mg m^{-2} d^{-1}) across the soil interface in the leachfield was calculated using the equation:

$$\Phi_X = [((R_X - R_{Cl})/100) \times (V_{STE} \times C_{X\text{-}STE})]/A/t \qquad \text{[Eq. 2]}$$

where R_X is the observed mean reduction for constituent X (%), R_{Cl} is the observed mean

Table 2. Estimates of bottom leachfield area, *A*, mean volume of septic tank effluent, *V*, dosed daily to a leachfield, and hydraulic load in Sites 1, 3, and 4. Values of *V* are assumed to be the same during Phase I and Phase II.

Site	Phase	A (m^2)	V (L)	Hydraulic load ($L\ m^{-2}$)
1	I	76.6	1440	18.8
	II	38.3	1440	37.6
3	I	24.5	1876	76.6
	II	12.3	1876	152.5
4	I	99.8	4686	47.0
	II	32.1	4686	146.0

reduction for chloride (%), V_{STE} is the mean volume of septic tank effluent applied to the leachfield (L), $C_{X\text{-}STE}$ is the mean concentration of constituent X in septic tank effluent (mg L^{-1}), A is the estimated basal area of leachfield (m^2) and t is time (d). This calculation assumes that Cl acts as a conservative tracer of the movement of STE through the soil, with apparent reduction attributed exclusively to dilution. Apparent constituent reductions larger than those observed for chloride are assumed to represent loss processes other than dilution (e.g. biological uptake, abiotic sorption); whereas reductions lower than observed for chloride are assumed to represent production processes (e.g. mineralization of organic compounds, desorption). Values of A prior to and after installation of SoilAir systems at Sites 1, 3 and 4 (Table 2) were estimated from design plans submitted to RIDEM as part of the original permitting process for septic system installation and knowledge of which trenches were isolated when the SoilAir system was installed. Values of V represent the mean of automated measurements of the volume of STE dosed daily to the leachfield and were assumed to be the same prior to and during operation of the SoilAir systems (Table 2).

Analyses

Septic tank effluent from pilot and field experiments was analyzed immediately for dissolved oxygen (DO). The temperature and concentration of Fe^{2+} of samples of STE and of water from mesocosms, wells and cup lysimeters were also determined immediately after sampling. All samples were assayed for pH immediately upon arrival to the laboratory before filtering. Unfiltered STE samples were assayed for biological oxygen demand (BOD_5) fecal coliforms and *Escherichia coli.* A portion of all unfiltered samples was frozen for subsequent determination of total N (TN) and total P (TP) content. The remaining sample was filtered by passing through a nylon membrane filter (MAGNA, 0.45-μm pore-size, 47-mm dia., Osmonics, Watertown, MA) and the filtered samples stored in plastic, screw-cap vials at 4°C.

Gases were sampled and analyzed using a portable soil gas monitor (SoilAir Technology, Killingworth, CT). CO_2, CH_4, O_2, and H_2S were determined using infrared, catalytic bead, galvanic, and electrochemical sensors, respectively. Gas samples were drawn at a rate of approximately 0.05663 $m^3\ h^{-1}$ (2.0 SCFH) for 30 to 60 s and the maximum values detected during that sampling period are reported for all gases except O_2, for which the minimum value is reported.

Constituent analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA, 1998). DO was measured using the azide modification of the Winkler titration method. The concentration of Fe^{2+} in water was determined using EM Quant ® Iron (Fe^{2+}) Test strips (EM Industries, Inc., Gibbstown, NJ). The pH of water samples was determined using a combination pH electrode and a model UB-10 pH meter (Denver Instruments, Denver, CO). The concentration of sulfate was measured using the barium chloride turbidimetric method. Nitrate, ammonium, and phosphate concentrations of water samples were determined colorimetrically using an automated nutrient analyzer (model Flow Solution IV, Alpkem, College Station, TX).

The total N and total P content of water samples was determined using the persulfate digestion method. Fecal coliforms and *E. coli* were assayed using the standard fecal coliform membrane filtration procedure. BOD_5 was measured on undiluted, unamended samples by manometric respirometry using an OxiTop® BOD system (WTW, Fort Myers, FL) at 21±1°C. The total organic carbon (TOC) content of filtered samples was determined using a TOC-5000A Total Organic Carbon Analyzer (Shimadzu Instruments, Inc., Laurel, MD).

Results

Pilot Scale Experiments

Experiment 1 – Effect of changes in headspace gas composition. This experiment was conducted to measure changes in the quality of water draining from lysimeters, as well as headspace gases and removal efficiencies for lysimeters when (1) conventional septic system leachfields are aerated by simulating the effects of SoilAir Technology (L→A) and (2) aeration is interrupted for an extended time (A→L). Within 63 days of the switch, the L→A treatment behaved like the AIR treatment , with water quality parame ters, removal efficiency for N, P, BOD and fecal coliforms, and the composition and concentration of headspace gases that were similar to those for the aerated treatment. The pH of effluent from the lysimeters became increasingly acidic (indicative of nitrification and supported by nitrate data) and DO levels were at or near saturation (Fig. 3). In addition, the speciation of inorganic N was similar to that for aerated mesocosms prior to the switch, with nitrate accounting for more than 90% of this pool (Fig. 3). Reduced iron was undetectable in drainage water, whereas sulfate concentrations were close to those in AIR mesocosm , after a large increase immediately after the switch (Fig. 3). The time required for these parameters to meet or exceed levels observed prior to the switch follows the order: Fe (1 d), DO (5d), SO_4 (47 d), NH_4 (63 d), NO_3 (63 d), pH (>63 d).

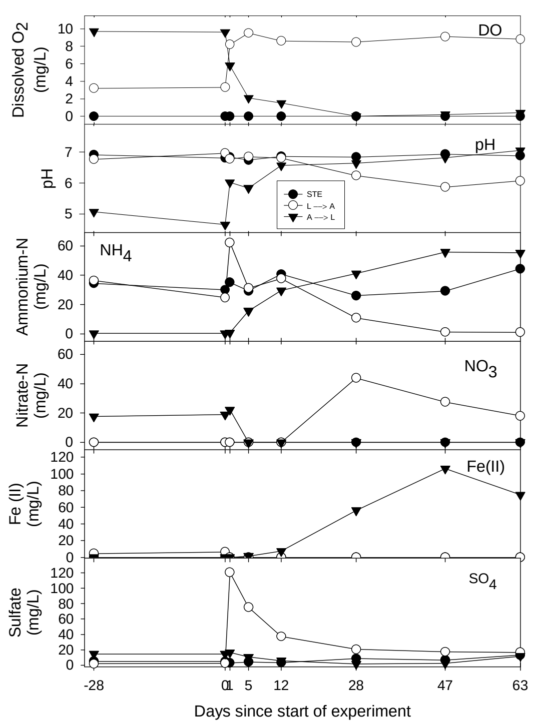

Fig. 3. Effects of changes in headspace gas composition of AIR and LEACH mesocosms on drainage water quality.

L→A lysimeters removed over 50% of the total N inputs, greater than 80% of the total P, and more than 99% of BOD_5 and fecal coliform bacteria 63 days after the switch (Fig. 4). These values were identical or exceeded the average values observed for aerated lysimeters prior to the switch (dashed line). The time required for these values to meet or exceed expected average levels of contaminant removal for aerated lysimeters prior to the switch (dashed line) followed the order: total P (1 d), fecal coliforms (5 d), BOD_5 (47 d), and total N (63 d).

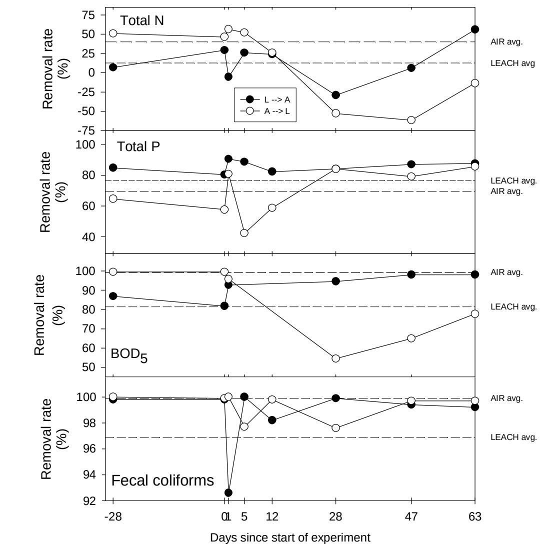

Fig. 4. Effects of changes in headspace gas composition of AIR and LEACH mesocosms on removal of total N, total P, BOD_5 and fecal coliforms.

The composition and concentration of headspace gases in the L→A treatment reached levels observed for aerated lysimeters prior to the switch 1 d after the switch for O_2, CO_2, H_2S and CH_4 (Fig. 5). Ponding, which had been prevalent in LEACH mesocosms (Fig. 6), disappeared within 5 days of the switch to aerated conditions in L→A lysimeters (Fig. 6).

Previously aerated lysimeters responded to the switch to leachfield gases (A→L) by generally behaving like the LEACH mesocosms prior to the switch. Levels of DO and pH values in drainage water from A→L mesocosms were similar to those for unaerated mesocosms prior to the switch (Fig. 3). The inorganic N pool was dominated by NH_4, with NO_3 completely absent from drainage water (Fig. 3). The concentration of sulfate was similar to that for LEACH lysimeters prior to the switch, whereas reduced iron levels were considerably higher than for unaerated lysimeters prior to the switch (Fig. 3). The time required for these parameters to meet or exceed levels prior to the switch followed the order: NO_3 (5 d), DO (28 d), NH_4 (28 d), pH (47 d), SO_4 (63 d), Fe (>63 d).

A→L lysimeters initially exhibited net loss of total N for part of the experiment, but N losses were near zero

Figure 4

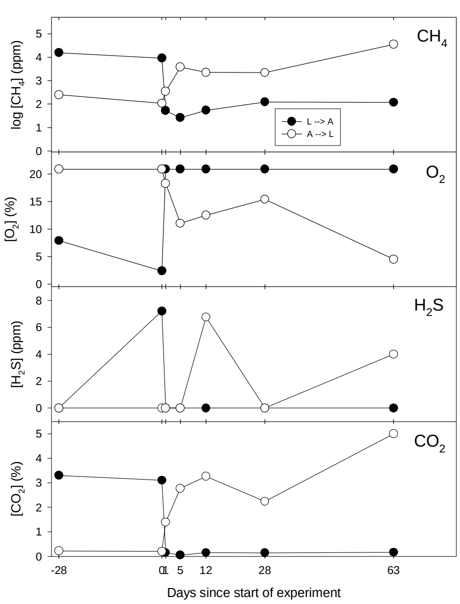

Fig. 5. Changes in headspace gas composition of AIR and LEACH mesocosms.

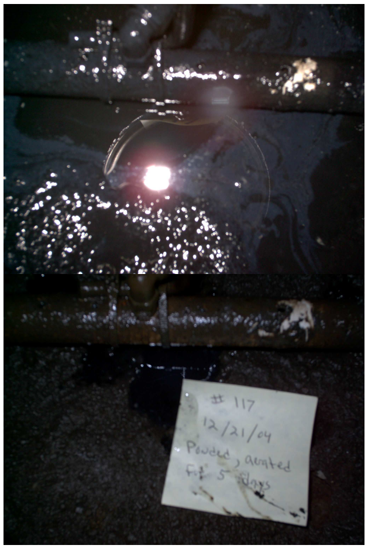

Fig. 6. Ponding was observed in LEACH mesocosms prior to aeration (TOP) and disappeared 5 days after the onset of aeration (BOTTOM).

63 d after the switch (Fig. 3). In contrast, total P removal was ~80% and reduction in BOD_5 was near that for LEACH mesocosms prior to the switch (Fig. 4). Removal of fecal coliforms reached levels observed for unaerated mesocosms. The time required to meet or exceed average values for unaerated mesocosms prior to the switch (dashed line) followed the order: total P (1 d), fecal coliforms (12 d), BOD_5 (>63 d), total N (>63 d).

The concentration and composition of headspace gases reached pre-switch values for all four gases (Fig. 5). The time required for headspace gas concentrations to meet or exceed levels observed prior to the switch followed the order: H_2S (12 d), CO_2 (12 d), CH_4 (63 d), O_2 (63 d). AIR lysimeters did not exhibit ponding prior to the switch. Once aeration was suspended, the A→L lysimeters became ponded 12 days after the switch.

Experiment 2 – Effects of loss of aeration. Levels of dissolved oxygen in water draining from the mesocosms diminished from ~8 to 4 mg/L at the end of the 48 h LOA period (day 2), but returned to previous levels once aeration was restored (day 3) (Fig. 7). The pH of drainage water was slightly lower in response to LOA, but returned to pre-LOA levels in response to restored aeration. LOA had no immediate effects on nitrate levels, although these were lower than pre-LOA levels in the latter part of the experiment. Ammonium levels remained low throughout the experiment. No Fe(II) was detected in drainage water prior to, during, or after the LOA event (data not shown). Levels of sulfate were also not affected by loss of aeration.

The effects of a simulated, accidental loss of aeration (LOA) for 48 h on the capacity of AIR lysimeters to remove carbon, nutrients, and fecal coliforms were quickly apparent (Fig. 8), but recovery was also quick. Removal of total N prior to LOA was near 45% - close to the average value observed for this treatment (Fig. 8). Within 24 h after the end of the 48 h LOA period (day 3), a statistically significant (repeated measures ANOVA vs. control; $P < 0.05$) net loss of N from these mesocosms

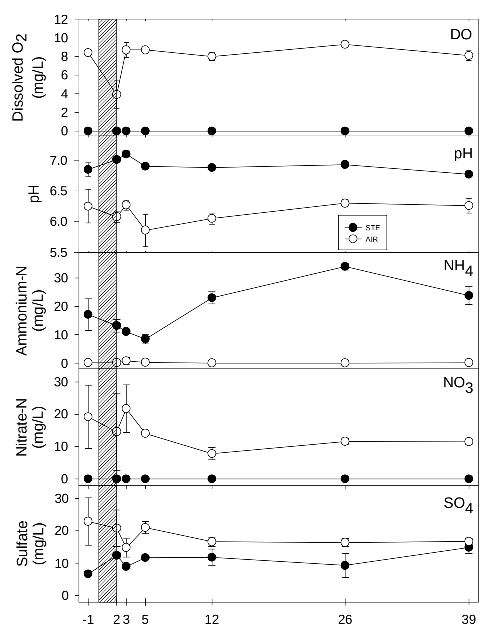

Fig. 7. Effects of short-term loss of aeration on water quality from AIR mesocosms.

was observed. However, 72 h after the end of the LOA period (day 5) net total N removal was observed again, and 10 days post-LOA (day 12) N removal was in the 60% range. Removal of N continued at or above the average value for AIR lysimeters subsequently.

Total P removal prior to LOA was about 70%, declining significantly at the end of the 48 h LOA period to a minimum of 50% (Fig 8). A return to P removal rates prior to LOA was observed within 10 days of restoring aeration (day 12), with above-average P removal observed subsequently.

BOD_5 removal rate declined from 100% to 93% at the end of the 48 h LOA period (Fig. 8) with considerable variation among replicate mesocosms, as indicated by the higher standard deviation observed on day 2, and thus was not statistically significant. Removal of BOD_5 returned to pre-LOA values 24 h after aeration was restored (day 3) and remained at that level for the remainder of the experiment.

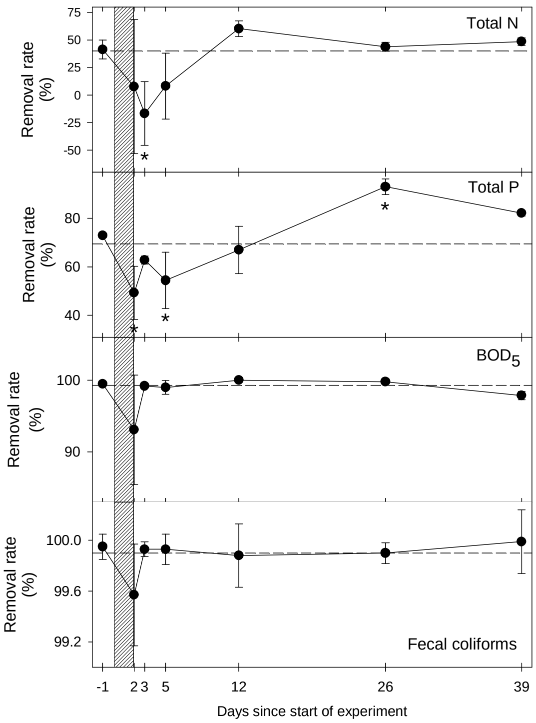

Fig. 8. Effects of short-term loss of aeration on removal of total N, total P, BOD_5 and fecal coliforms in AIR mesocosms. Bars represent 1 standard deviation. Shaded area indicates loss of aeration period. (*) indicates significant difference from initial value (P<0.05).

Removal rates for fecal coliform bacteria were on the order of 99.9% prior to LOA, and declined to ~99.6% by the end of the 48 h LOA period, although the effect was not statistically significant (Fig. 8). As observed for removal of BOD_5, the high standard deviation for fecal coliform removal on day 2 indicates that the response of lysimeters to LOA varied considerably among replicates. Fecal coliform removal rates were back to pre-LOA levels 24 h after aeration was restored, and continued

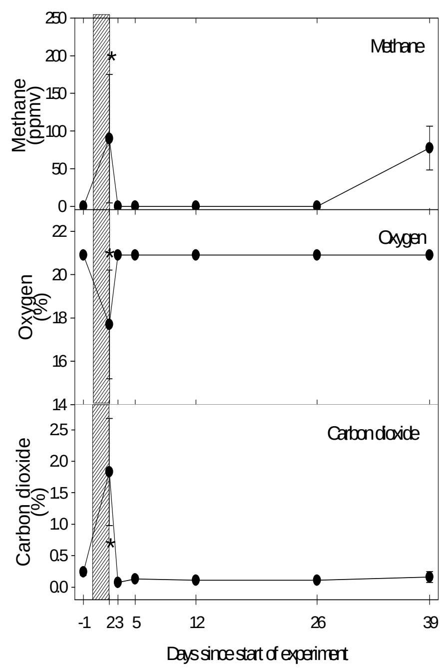

Fig. 9. Changes in headspace gas composition in response to short-term loss of aeration in AIR mesocosms.

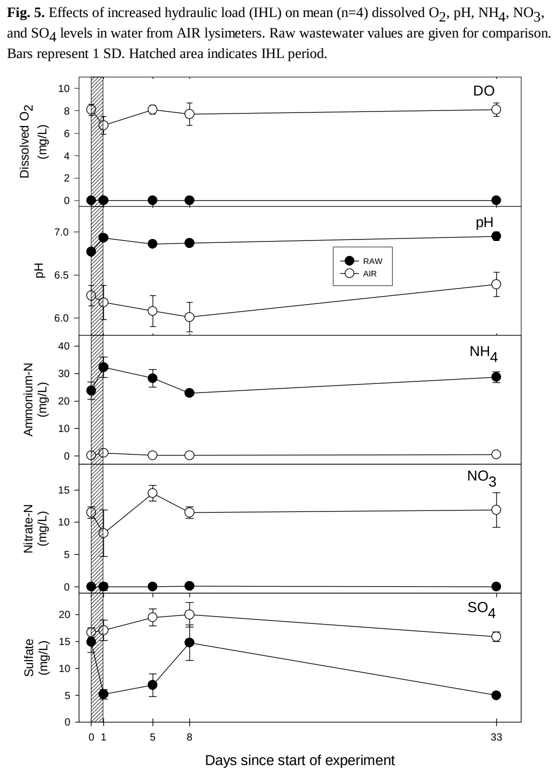

Fig. 10. Effects of increased hydraulic load (IHL) on water quality from AIR mesocosms. Shaded area indicates IHL period.

at that level for the rest of the experiment.

The composition and concentration of gases in the headspace of AIR mesocosms responded quickly to the LOA event and to restoration of aeration (Fig. 9). At the end of the 48 h LOA period (day 2), methane and carbon dioxide concentrations were significantly higher than observed prior to the event, while levels of oxygen were significantly lower (Fig. 9). Restoring aeration to the lysimeters resulted in levels of methane, oxygen, and carbon dioxide that were identical to those prior to the LOA event.

Experiment 3 – Effects of increased hydraulic load. Levels of dissolved oxygen in drainage water decreased in response to increased hydraulic load (IHL), returning to pre-event values within 4 days of switching to the initial loading rate of 12 cm d^{-1} (Fig. 10). Drainage water pH exhibited a small decline that continued for 7 days after the initial loading rate was restored, but was back to pre-IHL values 32 days after the event. Small fluctuations were observed in levels of ammonium and sulfate (increase) and nitrate (decrease) at the end of the 24 h IHL event, but the difference was not statistically significant, and levels of these constituents returned to pre-IHL event values within 7 days of returning to the initial the loading.

Increasing the hydraulic load from 12 to 24 cm/d had mixed effects on the ability of mesocosms to remove N, P, BOD_5 and fecal coliform bacteria. N removal increased in response to the IHL event (Fig. 11). Prior to the event, the total N removal rate was ~50%; at the end of the IHL period a statistically significant increase in N removal was observed, with 75% of the N input removed in AIR mesocosms. N removal rates remained at about 60% 4 and 7 days after the IHL event, returning to pre-event values after 32 days. No effect of IHL on removal of total P was observed (Fig. 11).

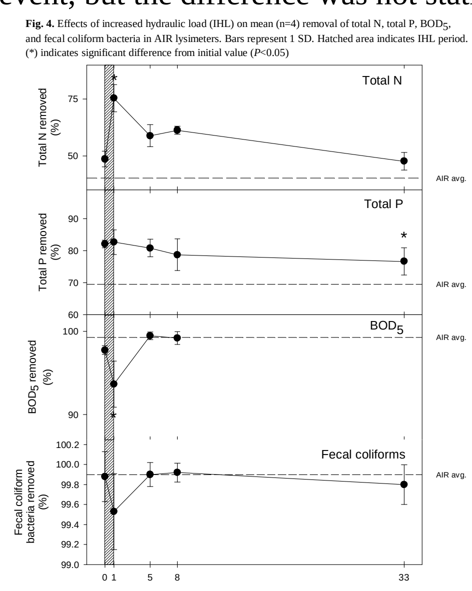

Fig. 11. Effects of increased hydraulic load (IHL) on removal of total N, total P, BOD_5 and fecal coliforms in AIR mesocosms. Shaded area indicates IHL period.

Table 3. Concentration and apparent reduction, *R*, for Cl, N, P, and TOC at Site 1 prior to (Phase I) and during (Phase II) operation of SoilAir system. Units for concentration are mg L^{-1}; units for *R* are %.

Constituent	Time period		STE	C2-30	C2-90	C3-30	C3-90
Cl	Phase I	Conc.	346.5	23.1	43.0	21.3	19.1
	(n = 7-14)	*R*	--	**93.3**	**87.6**	**93.9**	**94.5**
	Phase II	Conc.	314.0	34.6	127.1	100.0	123.1
	(n = 3-13)	*R*	--	**89.0**	**59.5**	**68.1**	**60.8**
N	Phase I	Conc.	42.6	11.8	9.4	12.6	6.4
	(n = 8-14)	*R*	--	**72.2**	**77.8**	**70.5**	**84.9**
	Phase II	Conc.	46.8	5.6	17.3	12.4	14.6
	(n = 6-13)	*R*	--	**88.1**	**63.0**	**73.4**	**68.8**
P	Phase I	Conc.	11.7	0.0	0	0	0.2
	(n = 9-14)	*R*	--	**99.8**	**100**	**100**	**98.3**
	Phase II	Conc.	13.3	0.0	0	0.1	0.9
	(n = 6-13)	*R*	--	**100**	**100**	**99.2**	**93.5**
TOC	Phase I	Conc.	107.3	0	0	0	0
	(n = 4-14)	*R*	--	**100**	**100**	**100**	**100**
	Phase II	Conc.	118.1	0	0	0	2.2
	(n = 1-13)	*R*	--	**100**	**100**	**100**	**98.1**

The IHL event had a statistically significant effect on the rate of BOD_5 removal (Fig. 11). Prior to the event, removal was at 99%, immediately after the event the rate dropped to 94%. The rate of BOD_5 removal returned to pre-event values within four days (day 5) and remained at that level for the rest of the experiment. Removal of fecal coliform bacteria also declined in response to the IHL event, although the effect was not statistically significant (Fig. 11). Removal rates were 99.9% before the event, and 99.5% immediately after. The fecal coliform removal rate returned to pre-event values within four days (day 5) and remained at that level for the rest of the experiment.

Lysimeter headspace gases were not affected by the IHL event (data not shown). No statistically significant differences in concentration of methane, oxygen, and carbon dioxide were observed pre- and post-IHL.

Field Scale Evaluation

Two sampling phases are distinguished for the purposes of comparing water quality parameters and gas composition in the field experiment. **Phase I** represents the period prior to installation of SoilAir systems between March and September of 2006. **Phase II** represents the period during which the SoilAir systems were monitored during in operation, from October 2006 until April 2007.

Table 4. Concentration and apparent reduction, *R*, for Cl, N, P, and TOC at Site 3 prior to (Phase I) and during (Phase II) operation of SoilAir system. Units for concentration are mg L^{-1}; units for *R* are %.

Constituent	Time period		STE	C2-30	C2-90	C3-30	C3-90
Cl	Phase I	Conc.	48.9	31.7	29.6	0	2.4
	(n = 5-14)	*R*	--	**35.2**	**39.6**	**100**	**95.2**
	Phase II	Conc.	44.8	24.5	41.4	0	14.7
	(n = 3-13)	*R*	--	**44.3**	**7.6**	**100**	**67.1**
N	Phase I	Conc.	42.4	28.4	23.2	9.7	13.7
	(n = 9-14)	*R*	--	**33.1**	**45.2**	**77.0**	**67.6**
	Phase II	Conc.	38.8	25.4	20.3	5.7	1.5
	(n = 4-13)	*R*	--	**34.6**	**47.8**	**85.2**	**96.1**
P	Phase I	Conc.	9.8	5.0	0	0	0
	(n = 9-14)	*R*	--	**49.6**	**100**	**100**	**100**
	Phase II	Conc.	11.1	6.4	0	0	0
	(n = 4-13)	*R*	--	**42.3**	**100**	**100**	**100**
TOC	Phase I	Conc.	101.6	0	0	0	0
	(n = 6-14)	*R*	--	**100**	**100**	**100**	**100**
	Phase II	Conc.	102.2	66.7	15.2	16.2	1.1
	(n = 3-13)	*R*	--	**34.7**	**85.1**	**84.2**	**98.9**

Values of concentration and percent reduction of Cl, N, P, and TOC at Sites 1, 3 and 4 prior to (**Phase I**) and during (**Phase II**) operation of the Soil Air system are shown in Tables 3, 4 and 5; data for Sites 2 and 6, in which SoilAir system was not installed, are shown in Tables 7 and 8. Actual removal rates for N, P, and TOC can be obtained by subtracting R_{Cl} for the appropriate time period.

Table 5. Concentration and apparent reduction, *R*, for Cl, N, P, and TOC at Site 4 prior to (Phase I) and during (Phase II) operation of SoilAir system. Units for concentration are mg L^{-1}; units for *R* are %.

Constituent	Time period		STE	C2-30	C2-90	C3-30	C3-90
Cl	Phase I	Conc.	53.5	26.8	38.7	37.8	41.4
	(n = 14-16)	*R*	--	**50.0**	**27.6**	**29.3**	**22.6**
	Phase II	Conc.	125.3	109.0	99.4	116.7	135.6
	(n = 3-11)	*R*	--	**13.0**	**20.7**	**6.9**	**-8.2**
N	Phase I	Conc.	35.8	16.3	22.9	25.0	26.6
	(n = 15-16)	*R*	--	**54.5**	**36.0**	**30.1**	**25.6**
	Phase II	Conc.	37.9	20.7	24.1	20.9	26.2
	(n = 4-11)	*R*	--	**45.4**	**36.4**	**45.0**	**30.8**
P	Phase I	Conc.	6.4	0.9	2.2	2.3	2.8
	(n = 16)	*R*	--	**86.2**	**65.5**	**64.6**	**56.2**
	Phase II	Conc.	9.1	2.4	2.7	2.8	3.4
	(n = 4-11)	*R*	--	**73.3**	**70.1**	**68.7**	**62.3**
TOC	Phase I	Conc.	77.5	26.4	50.9	41.8	52.1
	(n = 13-15)	*R*	--	**66.0**	**34.3**	**46.0**	**32.8**
	Phase II	Conc.	95.3	60.0	63.8	72.0	67.9
	(n = 3-11)	*R*	--	**37.1**	**33.1**	**24.4**	**28.7**

Of the sites without SoilAir, Site 6 exhibited the highest degree of N removal, with 6 to 52% removed at different points under the leachfield during Phase II. Similar reductions in N were observed at Site 2 during both time periods, with net N increases in some areas . Reductions in total P at Site 6 ranged from 13 to 77%, with values at Site 2 ranging from 9 to 73%, depending on position under the leachfield and time period evaluated. Removal rates for TOC at Site 6 ranged from 20 to 78% during Phase 1, with similar values observed during Phase 2. Considerably lower TOC removal rates were observed at Site 2 during both phases, with rates ranging from -16% (net increase in TOC) to 45% during Phase I and 1 to 16% during Phase II.

The most marked impact of the SoilAir system on reduction for N, P, and TOC was observed at Site 4, where values of R_X were similar for Phase I and Phase II, or were higher during Phase II (Table 5). For example, removal rates for N ranged from 1 to 8% during Phase I, whereas they ranged from 16 to 38% during Phase II. Phosphorus removal ranged from 36 to 45% during Phase I, with values of 50 to 70% observed during Phase II. TOC removal also increased during the operation of SoilAir, with removal rates of 7 to 16 % observed during Phase I, and 13 to 36% during Phase II.These results were observed despite the fact the system was operating using only 1/3 of the leachfield capacity available during Phase I and the mean concentration of N, P, and TOC in STE inputs was slightly higher during Phase II. Fluxes of N, P, and TOC at Site 4

Table 6. Concentration and apparent reduction, *R*, for Cl, N, P, and TOC at Site 6 prior to (Phase I) and during (Phase II) operation of SoilAir system. Units for concentration are mg L^{-1}; units for *R* are %.

Constituent	Time period		STE	C2-30	C2-90	C3-30	C3-90
Cl	Phase I	Conc.	258.3	253.2	245.2	281.2	265.4
	(n = 8-14)	*R*	--	**2.0**	**5.1**	**-8.9**	**-2.8**
	Phase II	Conc.	216.3	216.3	200.8	208.8	193.7
	(n = 5-13)	*R*	--	**0**	**0**	**0**	**0**
TN	Phase I	Conc.	54.2	47.3	48.1	31.5	45.5
	(n = 9-14)	*R*	--	**12.8**	**11.3**	**41.8**	**16.0**
	Phase II	Conc.	67.2	51.1	56.6	37.5	53.5
	(n = 6-13)	*R*	--	**24.0**	**15.7**	**44.2**	**20.4**
TP	Phase I	Conc.	11.9	10.0	9.3	4.3	5.1
	(n = 9-14)	*R*	--	**15.9**	**21.7**	**63.8**	**57.0**
	Phase II	Conc.	15.5	9.9	13.2	3.6	9.4
	(n = 6-13)	*R*	--	**36.2**	**14.8**	**76.5**	**39.5**
TOC	Phase I	Conc.	143.9	110.7	107.9	73.9	34.1
	(n = 8-14)	*R*	--	**23.1**	**25.0**	**48.7**	**76.3**
	Phase II	Conc.	151.5	111.1	110.2	104.2	25.5
	(n = 3-13)	*R*	--	**26.6**	**27.3**	**31.2**	**83.2**

(Table 6), which take into account differences in leachfield area and constituent concentration in STE between the two phases (Eq. 2), show that net removal of N, P and TOC was taking place prior to operation of the SoilAir system, as indicated by positive flux values. However, during Phase II, flux values were at least an order of magnitude higher than during Phase I for all three constituents.

Table 7. Concentration and apparent reduction, *R*, for Cl, N, P, and TOC at Site 2 prior to (Phase I) and during (Phase II) operation of SoilAir system. Units for concentration are mg L^{-1}; units for *R* are %.

Constituent	Time period		STE	C2-30	C2-90	C3-30	C3-90
Cl	Phase I	Conc.	58.4	49.7	51.5	48.1	51.4
	(n = 4-14)	*R*	--	**14.8**	**11.7**	**17.5**	**11.9**
	Phase II	Conc.	58.1	49.8	41.5	43.5	20.3
	(n = 2-13)	*R*	--	**14.1**	**28.4**	**25.0**	**65.1**
TN	Phase I	Conc.	50.7	37.7	39.0	38.0	19.7
	(n = 6-14)	*R*	--	**25.7**	**23.0**	**25.1**	**61.2**
	Phase II	Conc.	51.0	43.7	41.1	43.7	13.5
	(n = 1-13)	*R*	--	**14.3**	**19.4**	**14.2**	**73.6**
TP	Phase I	Conc.	11.3	4.2	1.8	2.0	1.9
	(n = 4-14)	*R*	--	**63.0**	**84.4**	**82.1**	**83.3**
	Phase II	Conc.	12.2	5.1	3.3	3.6	3.2
	(n = 1-13)	*R*	--	**58.2**	**72.7**	**70.9**	**74.1**
TOC	Phase I	Conc.	125.1	99.1	84.7	123.4	54.5
	(n = 2-14)	*R*	--	**20.8**	**32.3**	**1.4**	**56.5**
	Phase II	Conc.	124.6	104.8	82.8	85.0	35.2
	(n = 1-13)	*R*	--	**15.9**	**33.5**	**31.7**	**71.7**

Operation of the SoilAir system at Site 3 also appeared to have a positive effect on values of R_X for N, P, and TOC, which generally were either similar during both phases, or higher during Phase II despite a 50% reduction in nominal leachfield area (Table 4). The negative flux of N indicated net production at three of four points under the leachfield during Phase I, whereas net removal of N was apparent during Phase II in both of the lysimeters that sampled soil pore water 90 cm below the leachfield (Table 8). Phosphorus reduction at Site 3 was generally enhanced by operation of the SoilAir system, as indicated by positive flux values that were 2 to 15 × higher during Phase II (Table 6). Effects on TOC seemed to be mixed, with net reduction observed during Phase I at three of four points under the leachfield (Table 6). In contrast, at two of these points, negative flux values were observed for TOC during Phase II (indicating net production), but positive values that were 4 to 10 × higher than during Phase I were observed at lysimeters positioned 90 cm below the infiltrative surface (Table 8).

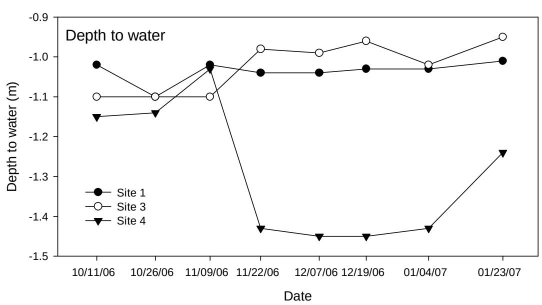

Fig. 12. Depth to water surface in the distribution box in Sites 1, 3 and 4. Values indicate distance from the ground surface.

Reduction of N, P and TOC were also impacted positively by operation of the SoilAir system at Site 1, with higher values of R_X observed despite a 50% reduction in leachfield capacity (Table 3). When con sidered in terms of constituent flux, operation of the SoilAir system appeared to make flux values for N less negative in three of four lysimeters, and positive (net removal) in the fourth (Table 8). Modest increases in P removal were observed between Phase I and II, with higher increases observed for TOC reduction during operation of the SoilAir system (Table 8).

Measurements of depth to water surface within the distribution box suggest that the hydraulic load at all three sites infiltrates readily, as indicated by the relatively constant, high depth values (Fig. 12). In all cases we observed levels of STE were at the invert during Phase II. Lower depth values for Site 4 during the early part of Phase II are due to a higher than normal hydraulic load from a leaking toilet. Variations in depth are the result of differences in timing of measurements relative to dosing events.

Table 8. Flux, Φ, of N, P, and TOC at different locations and depths under the leachfield of Sites 1, 3 and 4 prior to (Phase I) and during (Phase II) operation of SoilAir systems. Positive values represent constituent losses, negative values represent constituent gains.

Site	Phase	Lysimeter	Φ_N (mg N m^{-2} d^{-1})	Φ_P (mg P m^{-2} d^{-1})	Φ_{TOC} (mg TOC m^{-2} d^{-1})
1	I	C2-30	-170	10	140
		C2-90	-80	30	250
		C3-30	-190	10	120
		C3-90	-80	10	110
	II	C2-30	-20	60	490
		C2-90	60	200	1800
		C3-30	90	160	1420
		C3-90	140	160	1660
3	I	C2-30	-60	110	5,040
		C2-90	170	450	4,700
		C3-30	-710	0	0
		C3-90	-850	40	370
	II	C2-30	-630	-50	-1650
		C2-90	2380	1560	12080
		C3-30	-880	0	-2460
		C3-90	1720	560	4960
4	I	C2-30	80	110	580
		C2-90	140	110	240
		C3-30	10	110	610
		C3-90	50	100	370
	II	C2-30	1760	800	4380
		C2-90	830	660	2820
		C3-30	2080	820	3690
		C3-90	1670	830	5180

In general, operation of the SoilAir system at these three sites appeared to have a positive effect on the removal of N, P, and TOC, as indicated by improvements in constituent flux. In all cases, fluxes were positive for lysimeters positioned at 90 cm below the infiltrative surface, suggesting that net removal was taking place prior to discharge to groundwater (Table 8). Furthermore, normal hydraulic function was observed in all three sites (Fig. 12) despite increases in hydraulic load (Table 2).

Although many variables (e.g. differences in system configuration, soil, hydrology) are likely to contribute to differences among sites, we note that Site 4, which had a high hydraulic load during Phase II (Table 2), exhibited the greatest enhancement in terms of constituent flux, followed by Site 3, with a load similar to that for Site 4, and Site 1, with a hydraulic load nearly 4 $\times$ lower than at Site 4. A similar positive effect of high hydraulic loading on constituent removal rates was observed in laboratory experiments conducted earlier in the project. This suggests that laboratory results may have broad application to field conditions.

Discussion

The results of our pilot-scale studies suggest that introduction of intermittent aeration into leachfield soil under conventional non-aerated conditions can improve water quality functions, enhancing removal of N, fecal coliform bacteria, and BOD_5. These improvements were generally observed within four to eight weeks of the introduction of aeration. The performance of intermittent aeration technology also appears to be robust with respect to potential disturbances, such as temporary loss of aeration and increased hydraulic load. In response to a 48-h loss of aeration period, removal of total N, total P, BOD_5 and fecal coliform bacteria recovered to pre-disturbance levels within 1 to 10 days. Doubling the hydraulic load had the unexpected benefit of improving N removal rates immediately after the disturbance period. Removal of total P remained unaffected by the disturbance, whereas removal of BOD and fecal coliform recovered to pre-disturbance levels within 4 days.

Our results are consistent with the mechanisms thought to control constituent removal under intermittent aeration. For example, total N removal is thought to take place as a result of nitrification of NH_4 in leachfield during the aeration phase, followed by denitrification during infiltration of STE inputs, which provide organic C and anaerobic conditions that promote denitrification. Establishment of these conditions enhances N removal in previously unaerated leachfield soil, as we observed. Loss of aeration would be expected to have a negative impact on N removal, preventing oxidation of NH_4 to NO_3, a necessary step preceding denitrification. By contrast, increasing the hydraulic load probably enhances N removal as a result of longer periods of anoxia and inputs of organic C, which would support denitrification.

The modest effect of intermittent aeration on P removal suggests that the processes involved are somewhat dependent on the availability of oxygen. Phosphorus removal processes probably involve reaction with iron and aluminum oxides and oxyhydroxides, which are favored at pH values less than neutral observed in aerated soil. In addition, oxygenation of soil may prevent reduction of Fe(III) and associated release of bound phosphate.

The positive effects of intermittent aeration on removal of BOD_5 indicate that organic C metabolism in conventional leachfield soil is limited by the availability of O_2. Removing this limitation increased the ability of the microbial community to use the organic C compounds in STE inputs as well as those that form the restrictive layer, or biomat. As such, it enhances the infiltrative capacity of the system. Loss of aeration and increased hydraulic load apparently lowered levels of DO enough to impact BOD_5 removal. The mechanisms by which fecal coliform bacteria are reduced as a result of intermittent aeration are less apparent, but may involve increased numbers and predation by microbivorous fauna (e.g. protozoa and nematodes), which are more numerous when leachfield soil is aerated (Amador et al., 2006). As was observed with BOD_5 removal, lower fecal coliform removal may have been caused by the associated decreases in DO levels.

Data from the field evaluation of intermittent aeration indicates that it can improve the water quality function of failed conventional septic system leachfield. Removal rates for N, P, and TOC were comparable or higher than those observed prior to operation of SoilAir technology or to those observed at sites in which the technology was not installed. More importantly, these removal rates were achieved even though the nominal leachfield infiltrative surface area was reduced between 33 and 50%. When differences in infiltrative surface area are taken into account, introduction of intermittent aeration clearly improves the efficiency of leachfield soil in removing N, P, and TOC. In addition, intermittent aeration also appears to improve the infiltrative capacity of these systems, with normal hydraulic function observed despite reduced infiltrative surface area.

Comparisons with existing technologies are difficult to make because of its unique characteristics. For example, SoilAir appears to improve both infiltrative capacity and removal of nutrients and carbon simultaneously. Available alternatives for improving hydraulic function, such as cracking of soil with pressurized air, construction of a new leachfield, or resting an existing leachfield trench, do not address nutrient and carbon removal. Similarly, the alternatives currently available to improve the water quality function of OWTS address only the hydraulic function of a failed system, or often focus on a single wastewater constituent – nitrogen – and rely on soil absorption to remove other contaminants. Nitrogen removal technologies have been approved for us in Rhode Island and target 50% TN removal and a final concentration of 19 mg/L. However, strict adherence to operation and maintenance must be followed in order to consistently achieve these values. In instances where O&M is lacking, system performance is likely to suffer.

Our results from field and laboratory experiments suggest that SoilAir technology is a viable alternative for improvement of the water quality functions and concomitant restoration of hydraulic function in existing failed conventional leachfield trenches and sand filters, and it can do so at high loading rates. It may also be used to improve the water quality functions and extend the life of new and existing drainfields. Its simple design, ease of installation, and relatively low cost should make it an attractive technology to OWTS designers and installers, as well as homeowners. Widespread adoption may reduce inputs of pollutants into surface, ground and coastal waters from failed septic systems.

Utilization

a) End User Application

SoilAir was installed at three group homes owned by the RI Dept. of Mental Health, Retardation, and Hospitals. MHRH, in conjunction with George Loomis and David Kalen, from URI, identifying hydraulically failed OWTS in Washington County, RI that could be used for the study. After the number of sites was narrowed down, the necessary permits were obtained from RI DEM. Installation of the SoilAir systems was carried out by Geomatrix personnel in October of 2006 at no cost.

b) **Intellectual Property and Partnerships**

SoilAir technology was patented prior to the start of this study. Our project led to a successful partnership among the private sector (Geomatrix, LLC), academic researchers (URI's Laboratory of Soil Ecology and Microbiology) and experienced outreach professionals (URI's New England Onsite Wastewater Training Center) for testing and dissemination of information about SoilAir technology.

Knowledge Exchange

Publications - Abstracts:

Amador, J. A., J. H. Görres, E. L. Nicosia, and D. A. Potts. 2004 Microbiological and chemical properties of aerated and conventional leachfield soil. Abstracts of the Annual Meeting of the Soil Science Society of America, Seattle, WA.

Potts, D. A., M. C. Savin, P. Tomlinson, and J. A. Amador. 2004. Leachfield bacterial community structure as affected by aeration in septic tank effluent treatment. Abstracts of the Annual Meeting of the Soil Science Society of America, Seattle, WA.

Nicosia, E. L., J. A. Atoyan, D. A. Potts, and J. A. Amador. 2005. The fate of tetracycline in conventional and aerated septic system leachfield soils. *Abstracts of the ASA-CSSA-SSSA International Annual Meetings.* Available online at: http://crops.confex.com/crops/2005am/techprogram/P8950.HTM

Atoyan, J. A., E. L. Nicosia, D. A. Potts, and J. A. Amador. 2005. The effects of tetracycline on the microbial community of conventional and aerated leachfield soils. *Abstracts of the ASA-CSSA-SSSA International Annual Meetings.* Available online at: http://crops.confex.com/crops/2005am/techprogram/P8950.HTM

Richard, J. T., D. A. Potts, J. H. Görres, J. A. Amador, and B. Nowicki. 2005. Fate of ammonium in aerated and conventional septic system leachfield soil using stable nitrogen isotope tracer techniques. *Abstracts of the ASA-CSSA-SSSA International Annual Meetings.* Available online at: http://crops.confex.com/crops/2005am/techprogram/P8950.HTM

Publications - Proceedings

Amador, J. A., D. A. Potts, E. L. Nicosia, and J. H. Gorres. 2005. Aeration to improve the water quality and hydraulic functions of septic system leachfields. Proc. 13th Northwest On-Site Wastewater Treatment Short Course and Equipment Exhibition, Seattle, WA.

Publications - Peer-Reviewed Papers:

Amador, J. A., D. A. Potts, M. C. Savin, P. Tomlinson, J. H. Görres, and E. L. Nicosia. 2006. Mesocosm-scale evaluation of faunal and microbial communities of aerated and conventional septic system leachfield soils. *Journal of Environmental Quality* **35:**1160-1169.

Amador, J. A., D. A. Potts, E. L. Patenaude, and J. H. Görres. 2007. Effects of depth on domestic wastewater renovation in intermittently aerated leachfield mesocosms. *ASCE Journal of Hydrologic Engineering* (Accepted)

Atoyan, J. A., E. L. Patenaude, D. A. Potts, J. A. Amador. 2007. Effects of tetracycline on antibiotic resistance and removal of fecal indicator bacteria in aerated and unaerated leachfield mesocosms. *Journal of Environmental Science and Health, Part A* (In press)

Workshops:

15 March 2005	Amador gave a talk on the SoilAir system at a workshop for coastal decision makers entitled "Denitrification Systems: New Technologies and Alternatives to Traditional Septic Systems," co-sponsored by the Massachusetts Coastal Training Program and the Waquoit Bay Estuarine Research Reserve in East Falmouth, MA.
22 March 2005	OWT 105 - Innovative & Advanced Technology Overview Course. Led by Loomis and Kalen and attended by 16 professionals. SoilAir technology was introduced in this course as an experimental system.
23 June 2005	I & A Tour - Innovative & Advanced Technology Field Tour for Wastewater Professionals. Led by Loomis and Kalen and attended by 18 professionals
8 February 2006 8 March 2006	OWT 105 - Innovative & Alternative Technology Overview Course. Led by Loomis and Kalen and attended by a total of 61 professionals. SoilAir technology was introduced in both of these courses as an experimental system.
4 October 2006	OWT 105C Innovative and Alternative Technology Overview Led by Loomis and Kalen and attended by a total of 22 professionals. The SoilAir technology was introduced in both of these courses as an experimental system.

Conferences:

13 December 2004	Potts and Amador gave an invited presentation on the SoilAir system at the annual meeting of the Pennsylvania On-Site Wastewater Recycling Association in Harrisburg, PA.
19 September 2005	Amador gave an invited presentation entitled "Aeration to Improve the Water Quality and Hydraulic Functions of Septic System Leachfields" at the13th Northwest On-Site Wastewater Treatment Short Course and Equipment Exhibition, sponsored by the Univ. of Washington, Seattle, WA.
October 2005	Potts (Geomatrix) gave an invited presentation on "*Leachfield aeration for advanced treatment of domestic wastewater*" at the 14th Annual Technical Education Conference and Exposition of the National Onsite Wastewater Recycling Association in Cleveland, OH.
March 2007	D. Potts delivered a talk entitled "Effect of Aeration on a Failing Community Leach Field" at the Water for All Life Conference, 16th Annual Technical Exhibition and Conference & 1st International Conference, in Baltimore, MD.

Outreach Activities:

31 March 2005	Potts, Loomis, and Amador hosted a site visit by attendees at the 2nd Northeast Onsite Wastewater Treatment Short Course in Mystic, CT. Participants were given a tour of the Geomatrix pilot research facility in Westbrook, CT and of SoilAir systems in operation in southeastern CT.
2 April 2005	Amador and Gorres conducted a lab tour and 1-h inquiry exercise on water pollution by septic systems with a group of 15 middle school students that participate in the Rhode Island Science and Math Investigative Learning Experience (SMILE) program. Individuals in the SMILE program are academically-talented students that come primarily from economically-disadvantaged and/or minority households.
27 July 2006	"Cleaning up wastewater with dirt" A 1- hour, hands-on presentation by J. Amador on July 27, 2006 at the Earth Camp, W. Alton Jones Campus, University of Rhode Island, West Greenwich, RI. Approximately 12 campers, ages 11- 14, participated.

Literature Cited

Amador, J. A., D. A. Potts, M. C. Savin, P. Tomlinson, J. H. Görres, and E. L. Nicosia. 2006. Mesocosm-scale evaluation of faunal and microbial communities of aerated and conventional septic system leachfield soils. J. Environ. Qual. 35:1160-1169.

APHA, 1998. Standard methods for the examination of water and wastewater, 20th ed., APHA, Washington, DC.

Converse, J.C. and E.J. Tyler. 1994. Renovating failed septic tank-soil absorption systems using aerated pretreated effluent. In: Proceedings of the Seventh International Symposium on Individual and Small Community Sewage Systems. ASAE. St. Joseph, MI., pp. 416 – 423.

Gomez, A. L., and D. W. Urish, 1998. Determination of the quantity, quality, and location of coastal groundwater discharge to a marine embayment: Greenwich Bay, Rhode Island. Rhode Island Sea Grant College Program Technical Report No. RIU-T-98-005 (P1525); 100pp.

Kaplan, O. B. 1987. Septic systems handbook. Lewis Publishers, Chelsea, MI.

Potts, D. A. 2000. Method and Apparatus for Treating Leach Field. U S Patent 6 485 647. Date issued: 16 March.

Potts, D.A., J. H. Görres, E. L. Nicosia, and J. A. Amador. 2004. Effects of aeration on water quality from septic system leachfields. J. Environ. Qual. 33:1828-1838.

Rhode Island Department of Environmental Management (RIDEM). 2003. The Greenwich Bay Fish Kill - August 2003: Causes, Impacts and Responses [Online]. Available at http://www.state.ri.us/dem/pubs/fishkill.pdf (verified 13 Nov. 2003).

U. S. Census Bureau. 2003. 1999 American Housing Survey for the United States [Online]. Available at http://www.census.gov/hhes/www/housing/ahs/ahs99/tab1a4.html (verified 3 Nov. 2003).

U. S. Environmental Protection Agency (U.S. EPA). 2002. Onsite wastewater treatment systems manual. EPA/625/R-00/008. U. S. Environmental Protection Agency, Office of Water, Washington, DC.

Wigand, C., R. Comeleo, R. A. McKinney, G. Thursby, M. Chintala, and M. A. Charpentier. 2001. Outline of a new approach to evaluate ecological integrity of salt marshes. Hum. Ecol. Risk Assess. 7:1541-1554.