Stony Brook University

NITROGEN REMOVING BIOFILTERS
FOR ONSITE WASTEWATER TREATMENT ON LONG ISLAND:
CURRENT AND FUTURE PROSPECTS

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The New York State Center for Clean Water Technology

www.stonybrook.edu/cleanwater

Executive Summary

Recent research has demonstrated that the approximately 360,000 septic tank/leaching systems and cesspools that serve 74% of homes across Suffolk County have caused the concentrations of nitrogen in groundwater to rise by 50% since 1985. This nitrogen-enriched groundwater is flowing into sensitive coastal environments where it has contributed to toxic algal blooms, oxygen-deprived waters, the loss of seagrass and wetlands, the depletion of shellfish populations, and fish kills. In response to this environmental crisis, New York State recently established the NYS Center for Clean Water Technology (CCWT), whose primary objective is to develop and commercialize wastewater treatment systems for individual onsite (household) use that are affordable and highly efficient at removing nitrogen and other contaminants. The CCWT has identified Nitrogen Removing Biofilters (NRBs) as a system potentially capable of meeting this goal. NRBs are a form of passive wastewater treatment, which means they contain few moving parts (e.g., a single low pressure dosing pump) and operate largely by gravity, making them low-energy, low-maintenance and thus, low cost. Comprised of a sand-based "nitrification layer" underlain by a "denitrification layer" of sand mixed with finely ground wood, the system is installed following a standard septic tank/pump chamber combination and is intermittently dosed by a low pressure distribution system. In full-scale pilot studies investigated by the CCWT, these systems have demonstrated an ability to consistently achieve high percentages of total nitrogen removal (up to 90%), as well as efficient attenuation of pathogens, pharmaceuticals and personal care products. While data from a range of installations in local conditions are necessary to assess system performance, these preliminary results are encouraging. Similar in footprint and basic functionality to a drain field, the common form of dispersal for septic tank effluent across the nation, the incorporation of locally sourced sand and wood media aims to position the system as an economically viable alternative for high efficiency onsite wastewater treatment with a performance longevity of multiple decades. Further, the shallow profile of these systems (< 4 feet) would make them a suitable option in regions with shallow water tables, which are prevalent across Long Island, and increasingly common as sea levels continue to rise. However, system footprint will be a limiting factor, making it unsuitable for certain small lots. In light of these findings, the CCWT is preparing to pilot a series of NRB configurations in collaboration with the Suffolk County Department of Health Services. This process that will assess the effectiveness of the system in a range of dynamic conditions and lead to a more refined understanding of the complex processes occurring within the systems; an effort that will inform the suitability of the approach for widespread use on Long Island.

Introduction

The quality of life on Long Island hinges upon the quality of its groundwater and surface waters. Groundwater is Long Island's only source of drinking water, thus contamination of the aquifer poses a threat to human health. Further, contamination of Long Island surface waters has the potential to affect economic prosperity, as well as public health and safety. Coastal pollution from excessive nitrogen on Long Island is contributing toward toxic algal blooms, oxygen-deprived waters, the loss of seagrass and wetlands, the depletion of shellfish populations and fish kills. These deleterious impacts are directly and indirectly linked to nitrogen loading to coastal waters via submarine groundwater discharge (NYSDEC 2009, 2015; Sunda and Gobler, 2012; Gobler et al., 2012; Hattenrath et al., 2010; Hattenrath-Lehmann et al., 2015; Tomarken et al., 2016). Additionally, recreational fishing, commercial fishing, tourism, and recreational boating each represent billion dollar industries in Suffolk County alone (SCCWRMP, 2015). It is estimated that 60% of the Long Island economy depends on clean water (TNC, 2015) and that property values in Suffolk County are linked to water clarity (Smith and Dvarskas, 2016).

Because of the key role nitrogen has played in the degradation of coastal resources, nitrogen budgets have been developed for Long Island's north shore, south shore, and east end, all of which demonstrate that the largest source of nitrogen from land to coastal waters is household septic systems (Kinney and Valiela, 2011; Lloyd, 2014, 2016; Stinnette, 2014). Given these findings, Suffolk County Executive Steve Bellone recently declared nitrogen pollution from septic systems on Long Island "Public Water Enemy #1" (SCCWRMP, 2015). Suffolk County has approximately 360,000 septic tanks and leaching rings, and/or cesspools that service 74% of residential homes (SCCWRMP, 2015). Cesspools, also called cesspits, leaching rings, or leaching pools are designed to facilitate rapid dispersal of household sewage within the soil (Figure 1A). Beneath the cesspool where conditions are oxidizing, the ammonia in household wastewater is converted to nitrate (NO_3^-), a process known as 'nitrification'. Under conditions characteristic of Long Island's surficial aquifers, nitrate is highly stable and persistent in groundwater. This excess nitrate can potentially contaminate drinking water supplies and eventually discharges to Long Island's sensitive coastal waters (Figure 1A).

Although uncommon on Long Island, the most common mode of onsite wastewater disposal in the United States transports septic tank effluent to shallow drain fields or leach fields that run horizontally approximately 6-8 inches below the surface. These systems are designed using soil properties and characteristics to create conditions that allow for more nitrogen and other contaminants to be removed from

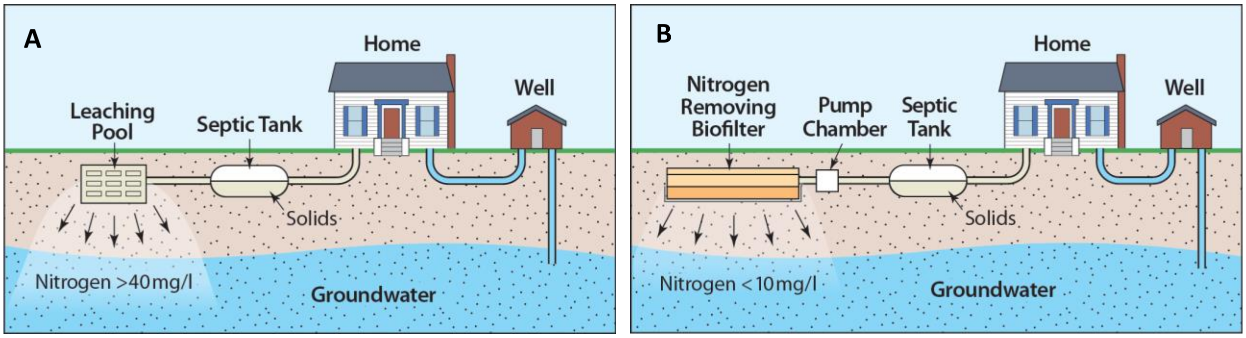

Figure 1. A) Conceptual schematic of the input of nitrogen from leaching pits to groundwater on Long Island. This nitrogen-rich groundwater can enter coastal zones, leading to harmful algal blooms and fish kills. B) Conceptual schematic of Nitrogen Removing Biofilter (NRB). Note significantly decreased nitrogen concentrations entering groundwater.

wastewater by plants and microbes than is possible in deep leaching pools. However, NRBs differ from standard drain fields in that they consist of an integrated design to remove large amounts of nitrogen via the microbial processes of nitrification and denitrification, and thus can be viewed as a completely new type of household wastewater treatment system.

NRBs typically consist of a layer of sand or sandy soils overlying a layer of sand mixed with finely ground wood that is dosed by a low pressure distribution system. In pilot phase testing of full-scale systems, NRBs have demonstrated an ability to achieve high percentages of nitrogen removal (up to 90%), as well as significant attenuation within the nitrifying layer of pathogens, pharmaceuticals and personal care products (PPCPs), including DEET, Bisphenol A, Nicotine, Acetaminophen, Caffeine, Ibuprofen, Warfarin, and Acesulfame K (Heufelder, 2015, CCWT, in progress). Later in this report, we describe in detail the biogeochemical steps by which nitrogen is efficiently removed from wastewater in these systems.

As a form of passive wastewater treatment, NRBs are designed with few moving parts (e.g., a single low pressure dosing pump) and operate largely by gravity, making them low-energy, low-maintenance and thus, low-cost. The system follows a standard septic tank/pump chamber combination and is comprised of locally sourced sand and wood media (lignocellulose), which contributes to cost management. Longevity of the wood media, which is used as a carbon source for denitrification, is estimated at multiple decades (Robertson et al., 2009; Robertson, 2010). For example, stoichiometric calculations by the CCWT for a proposed NRB design indicate the recommended quantity of wood media contains more than 100 years of available carbon for biological nitrogen removal. Further, mass balance calculations by Robertson based on a pilot installation indicated that only 10% of the wood material was consumed after 7 years of denitrification, supporting the claims of field studies indicating that wood particle media can deliver stable nitrogen removal over decades. As pointed out by Robertson (2010), this confirmation of multi-year longevity should enhance the attractiveness of wood chip media for use in denitrifying bioreactors when very long-term maintenance-free applications are desired.

This report summarizes the current state-of-knowledge regarding NRBs, providing in-depth detail and references on the functioning, history, and current applications of the approach. We conclude with a summary of a recent “design charrette” organized by the NYS Center for Clean Water Technology, which brought together the leading experts in this field to identify the optimal configurations of this technology for Suffolk County. We further comment on the anticipated steps the NYS Center for Clean Water Technology is taking, in collaboration with the Suffolk County Department of Public Health, to evaluate the suitably of the approach for deployment on Long Island.

Description of System Function and Performance: Nitrification and Denitrification

The removal of nitrogen in a NRB involves two steps: 1) a nitrification step in which ammonia and reduced organic nitrogen in septic tank effluent is converted to nitrate in an unsaturated, oxygen (O_2) rich sand layer, followed by 2) a denitrification step in which nitrate is converted to nitrogen gas in a semi-saturated to saturated, O_2-limited sand plus lignocellulose (wood chips or sawdust) layer. In NRBs, the delivery of septic tank effluent over the top of the treatment unit occurs via a low pressure distribution system comprised of a low-energy pump and several parallel, low pressure dosing pipes with drilled orifices (Figure 2A), followed by infiltration (i.e., gravity and capillary water movement without active pumping). The processes leading to nitrification and near complete denitrification in a NRB are described in detail below, and illustrated in Figure 2B.

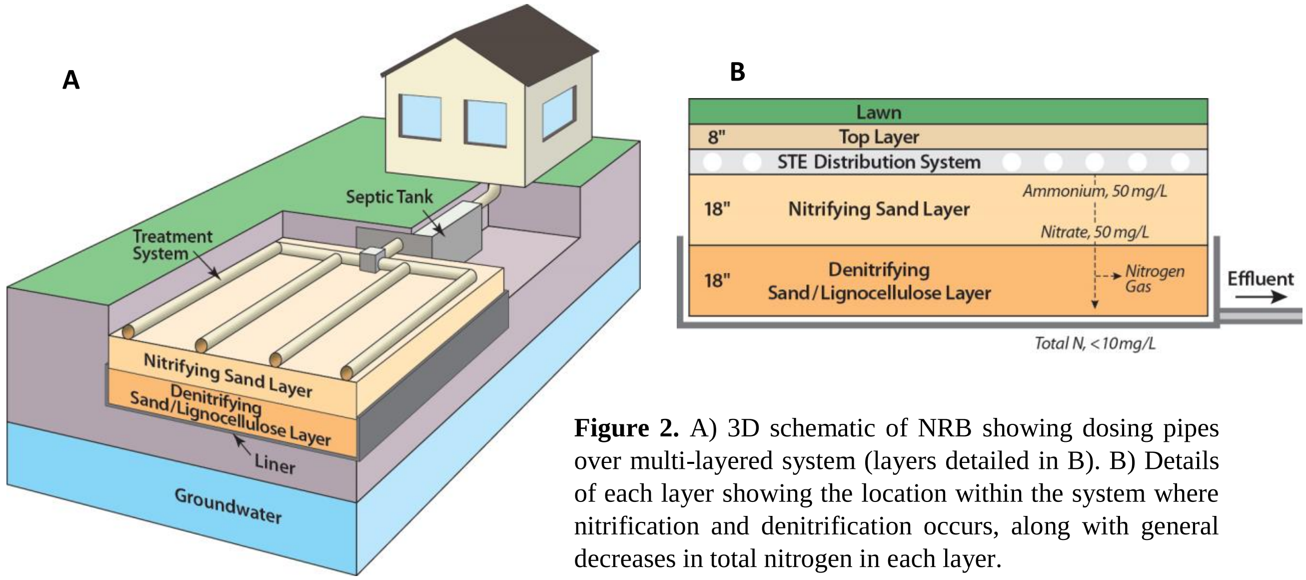

Figure 2. A) 3D schematic of NRB showing dosing pipes over multi-layered system (layers detailed in B). B) Details of each layer showing the location within the system where nitrification and denitrification occurs, along with general decreases in total nitrogen in each layer.

Nitrification in a NRB

Generally, most of the nitrogen exiting a septic tank is in the form of organic nitrogen and ammonium (NH_4^+). Solids and fluids are separated in the septic tank, and the fluids, enriched in ammonium, will enter the top of the NRB via a pressure dispersal system as described above. From this point ammonium is oxidized to nitrate as it percolates through the upper sand or sandy soil layer. This has traditionally been inferred to follow a two-step process facilitated by chemolithoautotrophic bacteria, although we are learning that other processes may play a role (see below). During the first step, three main genera of chemolithoautotrophic bacteria (*Nitrosomonas*, *Nitrosococcus*, and/or *Nitrosospira)* convert ammonium to nitrite (NO_2^-). The second step, driven by *Nitrospira*, *Nitrospina* and *Nitrobacter* bacteria, results in the conversion of nitrite to nitrate (USEPA, 1993; Hazen and Sawyer, 2016). Since this is a chemolithoautotrophic process, bacteria do not need organic carbon but instead use an inorganic compound (e.g., carbon dioxide (CO_2)) as the carbon source and derive energy by oxidizing reduced compounds (e.g., ammonium is typically the electron donor and oxygen is the electron acceptor; Metcalf & Eddy, 2014; Hazen and Sawyer, 2016).

It is unclear how some parameters, including alkalinity (i.e., the capacity of an aqueous solution to neutralize an acid) and temperature, can influence the rates of nitrification reactions in NRBs. For example, nitrifying bacteria are sensitive to cold temperatures, and therefore reactions may be slower during winter months. Further, although the above stated processes are dominant in the upper sand layers of NRBs, other processes also may occur including the anaerobic ammonium oxidation (ANAMMOX), denitrification and N_2O production in this unsaturated layer. These are a few of the questions the CCWT aims to address.

Denitrification in a NRB

After passing through the upper sand layer of the NRB, most of the nitrogen is converted to nitrate which passes through a layer of sand mixed with lignocellulose (e.g., wood chips and/or sawdust). The sand-lignocellulose layer provides the carbon source for denitrification to occur while mixing with a soil texture with the capacity to promote anaerobic conditions (Robertson and Cherry, 1995). A liner can also be added to achieve saturated soil conditions, which are likely to maximize the success of denitrification and the longevity of the lignocellulose. Denitrification is facilitated by a wide diversity of bacteria that can oxidize soluble organic substrates (e.g., wood chips) via the reduction of nitrate and/or nitrite as electron acceptors. The conversion of nitrate to dinitrogen gas (N_2) takes place in several steps, generally as follows: nitrate → nitrite → nitric oxide → nitrous oxide → dinitrogen gas. If the conditions for denitrification exist (i.e., sufficient carbon and lack of oxygen), then the nitrified effluent from the nitrification layer will be converted to N_2 gas and released to the atmosphere. However, it is important to note that if the sequence is interrupted, nitric oxide (NO) and/or nitrous oxide (N_2O) can be produced (Hazen and Sawyer, 2016).

The microorganisms facilitating the denitrification reactions do so either heterotrophically (i.e., using organic carbon as an electron donor) or autotrophically (using inorganic compounds such as sulfur, iron or hydrogen as an electron donor). Both pathways are possible in NRBs as long as anoxic conditions (no free oxygen) are maintained. Heterotrophic bacteria convert nitrate nitrogen to nitrogen gas in the process of organic carbon oxidation according to the following reaction (Schmidt and Clark, 2012):

$$5C_6H_{12}O_6 + 24NO_3^- + 24H^+ \rightarrow 12N_2 + 42H_2O + 30CO_2$$

While biological denitrification is well understood, the microbial ecology of these system is complex. For example, there is evidence of denitrification occurring in the nitrification layer. These are interactions the CCWT is tasked with understanding, and improving.

A Brief History of NRB Design

One of the first designs of a NRB was developed by Robertson and Cherry (1995). The reactive organic material consisted of sawdust, which promoted nitrate removal by heterotrophic denitrification. Robertson and Cherry (1995) emphasized that saturation in their NRB was required in order to achieve anoxia. Further, the sawdust or lignocellulose provided the carbon source and removal of O_2 by bacteria, and when mixed with silt also achieved anoxic conditions through reduction of flow. Since this first design for NRBs incorporating lignocellulose, several improved designs have been demonstrated, including those associated with the Florida Onsite Sewage Nitrogen Reduction Study (FOSNRS), and work carried out at the Massachusetts Alternative Septic System Test Center (MASSTC). Here we provide a summary of these latter investigations.

Florida Onsite Sewage Nitrogen Reduction Study (FOSNRS) (Anderson and Hirst, 2015)

The Florida Onsite Sewage Nitrogen Reduction Study (FOSNRS) examined a NRB consisting of two stages as described above with an upper sand layer for nitrification and a lower lignocellulose layer for denitrification (Anderson and Hirst, 2015a, 2015b; Hazen and Sawyer, 2015; Anderson, et al., 1985). The nitrification material used was a ‘clean fine sand,’ a native soil type readily available in Florida. The results from this study indicated near-complete nitrification of percolating wastewater prior to passing through the wood-containing (lignocellulose) matrix. Where extremely low TN (<3 mg/L) was mandated, the percolate was directed through a container of elemental sulfur for additional removal of nitrate after passing through the two stage system. The direction and redirection of percolating wastewater was enhanced by the use of impervious liners that were sloped in various manners and had drains that also collected and diverted the percolate. The initial designs used drip dispersal systems for the delivery of septic tank effluent to the top of the system.

One of the first designs constructed by FOSNRS was a pilot-scale vertically-stacked passive nitrogen reduction system (Anderson and Hirst, 2015b). This system was an approximately 1/10 scale model designed for testing purposes. The configuration consisted of drip irrigation (dosed 24 times per day), a sand nitrification layer, and a sand/lignocellulose layer (50/50 by volume). The sand/lignocellulose layer was placed over a poly-liner with an underdrain collection pipe, which directed effluent to an upflow elemental sulfur denitrification biofilter and a final infiltration system. In summary, the treatment sequence was as follows: septic tank effluent → drip dispersal system → 18 inches of fine sand (for nitrification) → 2-9 inches of a wood chips / sand mix → collected and diverted through an elemental sulfur biofilter → final dispersal through a chamber drainfield trench. This system configuration, which was mounded due to permitting restrictions in Florida related to height above the water table, is shown in Figures 3A and 3B.

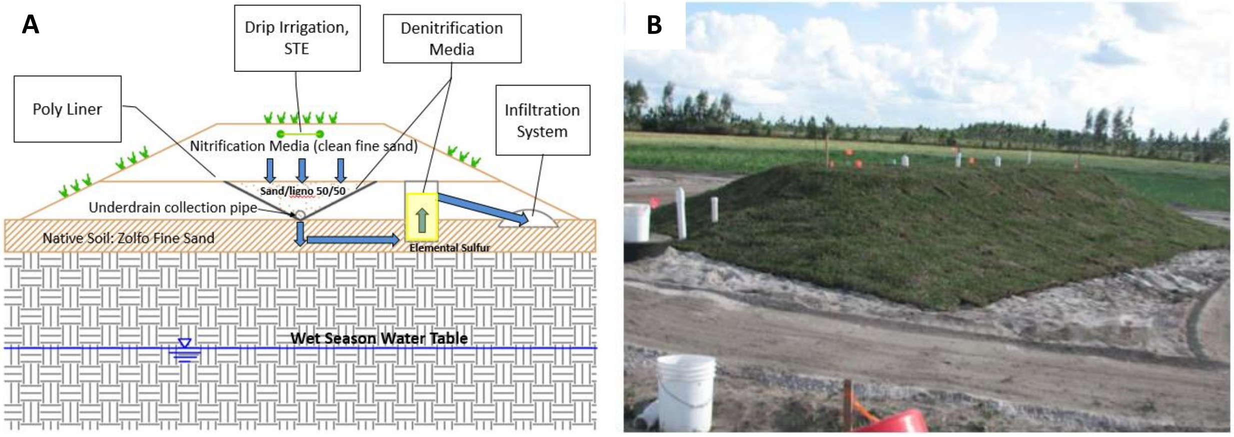

Figure 3. A) Simplified schematic of a FOSNRS design (modified from Anderson and Hirst, 2015b; Hazen and Sawyer, 2015). B) Photograph of final installation.

Both the short and long term results from this study were very promising. For example, total nitrogen was reduced from approximately 65 mg/L TN to 3.5 mg/L, or 95% reduction (Figure 4). Up to 90% reduction of TN was achieved using only the lignocellulose layer (i.e., prior to passage through the elemental sulfur layer) indicating the sand-wood mix removed a large majority of the nitrogen and that the sulfur layer had a very minor contribution to nitrogen removal. This pilot study was carried out over nearly 1.5 years, with consistent reduction in TN (Figure 4).

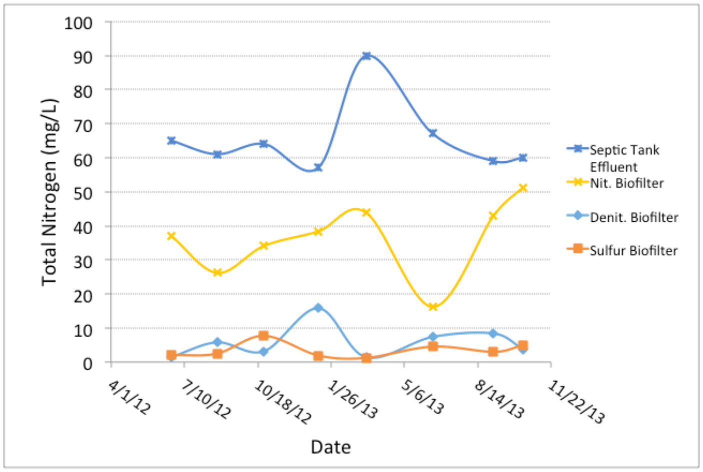

Figure 4. Total nitrogen (TN) concentrations over time for each layer in the FOSNRS mounded PNRS compared to septic tank effluent TN (modified from Anderson and Hirst, 2015b).

Based on the initial success of the 1/10 scale pilot, as well as a larger scale test installation with similar results, a full-scale system was installed at a residential home in Seminole County, FL. This system was similar in configuration consisting of a layered biofilter system (Figure 5A; designed for 580 gallons per day (gpd) dispersal across 728 square feet (SF) drip for treatment; i.e., 0.8 gpd/SF). The actual dosage from the home averaged 117 gpd, with a final loading rate only of 0.16 gpd/SF. The configuration incorporated an 18” layer of sand over a 2-9” layer of lignocellulosic/sand mix (50/50; Stage 1), and 12” sulfur & oyster shell mix at a 90/10 ratio in an upflow denitrification biofilter tank (Stage 2). This design incorporated a single pump, which alternated between two dispersal fields.

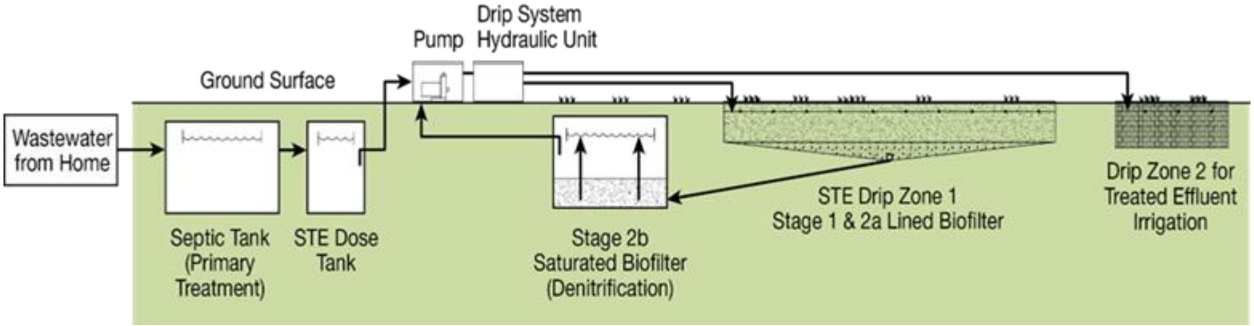

Figure 5. A) Configuration of first full scale FOSNRS system installed in residential house (Hazen and Sawyer, 2015).

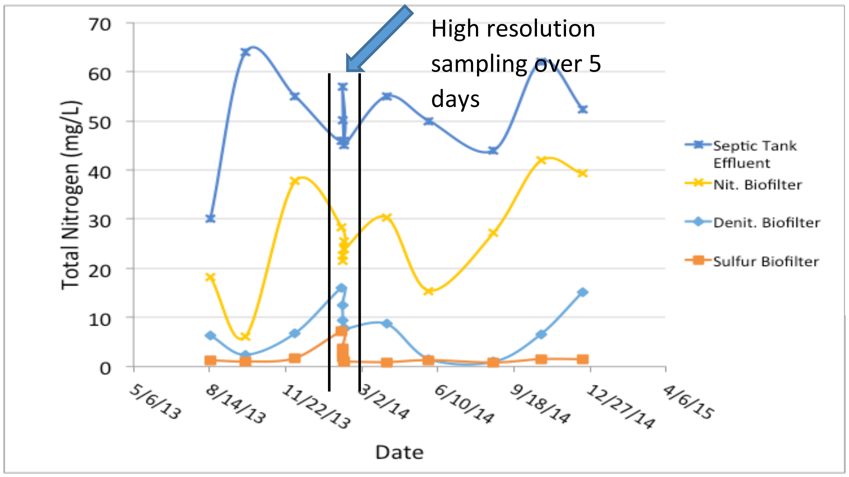

Figure 5. B) Total nitrogen (TN) concentrations over time for each layer in the FOSNRS full-scale system. STE = septic tank effluent (modified from Anderson and Hirst, 2015b).

Florida's goal for total nitrogen in the effluent of an individual, on-site treatment system in some nitrogen sensitive areas is as low as 3 mg/L. The initial results from this full-scale system exceeded this objective. For example, the influent concentration averaged 50.5 mg/L TN, and was reduced to 25.4 mg/L TN in the sand layer (50%), to 7.9 mg/L in the lignocellulose/sand layer (84%), and finally to 1.9 mg/L for the final concentration after the sulfur layer for a 96% reduction in total nitrogen (Figure 5B). Again, the large majority of the nitrogen removal in this system was within the sand and sand-wood layers. Over the long term, TN in effluent from this system was consistently less than 10 mg/L (Figure 5B). These and similar successes by FOSNRS led to the testing of similar systems in Massachusetts, as described below.

The Massachusetts Alternative Septic System Test Center (MASSTC)

The Massachusetts Alternative Septic System Test Center (MASSTC), located in Barnstable County, Massachusetts, and run by the Barnstable County Department of Health and Environment, is currently performing full-scale trials of NRBs incorporating wood chip-sand mixtures (Heufelder, 2015). The goal of these studies has been to determine the simplest, most cost-effective modification of a soil absorption system to enhance nitrogen removal in Cape Cod's geological setting. MASSTC utilizes the wastewater stream generated at the nearby Otis Air National Guard Base on the Massachusetts Military Reservation. Data collected from these NRB's show total nitrogen concentrations consistently below 10 mg/L (Heufelder, 2015).

MASSTC's first exploration of NRBs involved the use of large plastic columns supplied with influent from an adjacent wastewater stream in order to generate the information needed to properly design full-scale installations. Septic tank effluent was first passed through an 18" soil profile of loamy sand to convert ammonium to nitrate. In addition to nitrification, this step also resulted in an up to 50% decrease in TN, suggesting that some unexplained process, perhaps aerobic denitrification, is occurring in the nitrification layers. This was then supplied to columns filled with 18” of a 50/50 sand-sawdust mix (Figure 6A). Both saturated and unsaturated configurations were tested (Figure 6B). The saturated systems were plumbed to maintain saturated conditions within the wood-sand layer. The unsaturated systems allowed for the wastewater to directly pass through the wood-sand layer. The results from the saturated system indicate significant reduction in TN occurred consistently over a 23-month period (Figure 6C). TN concentrations decreased from approximately 20-30 mg/L in septic tank effluent, to consistently below 5 mg/L in the last year of the experiment. Although less TN removal was achieved in the unsaturated system over time, greater than 50% removal was achieved (Figure 6D). Note a decrease in TN up to 50% in the nitrified effluent used to dose the sand/sawdust mix.

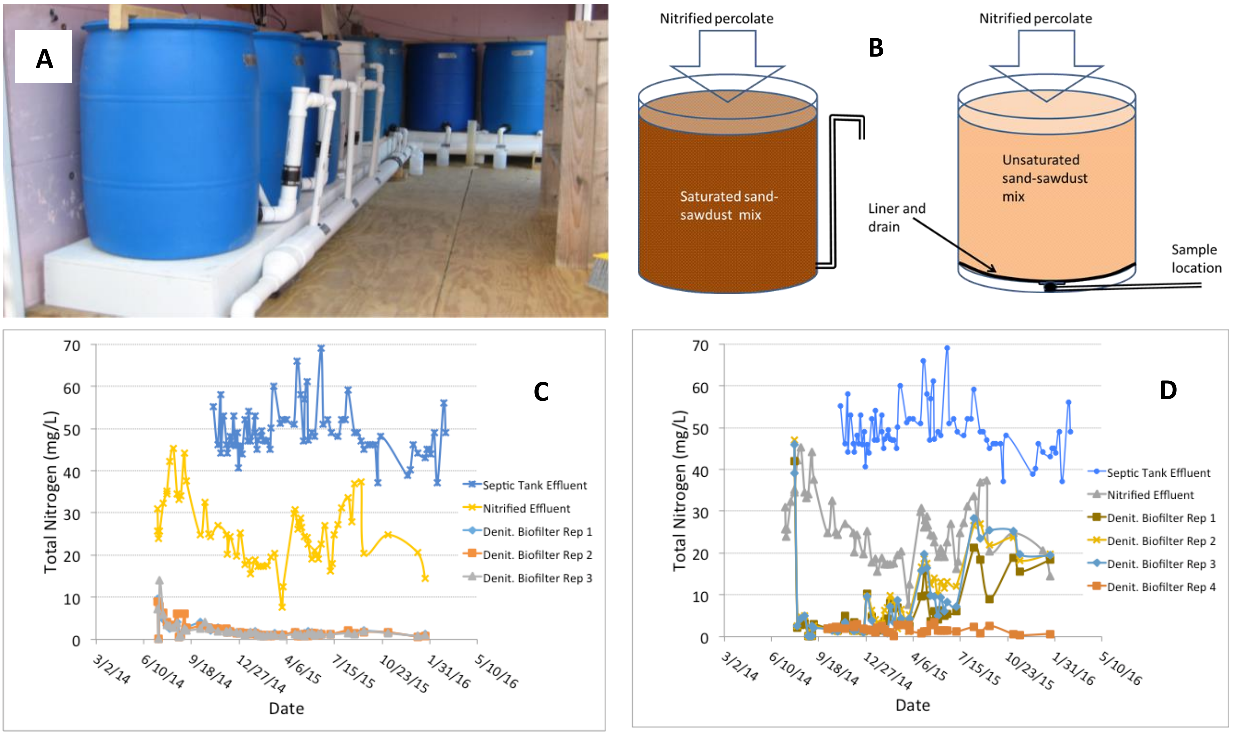

Figure 6. A) Photograph of pilot scale MASSTC column denitrification system. B) Schematic showing saturated versus unsaturated configurations. These configurations only test the denitrification process. Previously nitrified effluent is added to the top of each column. Note that TN is decreased by ~50% in the nitrified effluent. C) TN concentrations over time for saturated column compared to septic tank effluent and previously nitrified effluent. D) TN concentrations over time for unsaturated systems compared to septic tank effluent and previously nitrified effluent. Each configuration was tested with multiple replicates, shown as “Rep” followed by the number.

Building on initial results from the first column studies, the second test configuration consisted of a small-scale, unsaturated, in-ground NRB installation. This configuration consisted of an ultra-shallow low pressure distribution system over an 18” layer of loamy sand overlying an 18” 50/50 sand-sawdust layer (Figure 7A). Approximately 50 mg/L TN was reduced to a mean of 5.6 mg/L (median = 3.3 mg/L) over a 16-month period (Figure 7B). The results indicated that denitrification rates depended on temperature. It was hypothesized that cold percolate in the winter carried more oxygen to the denitrification layer, thus decreasing the rate of nitrogen removal. In addition, colder temperatures likely slow microbial processes.

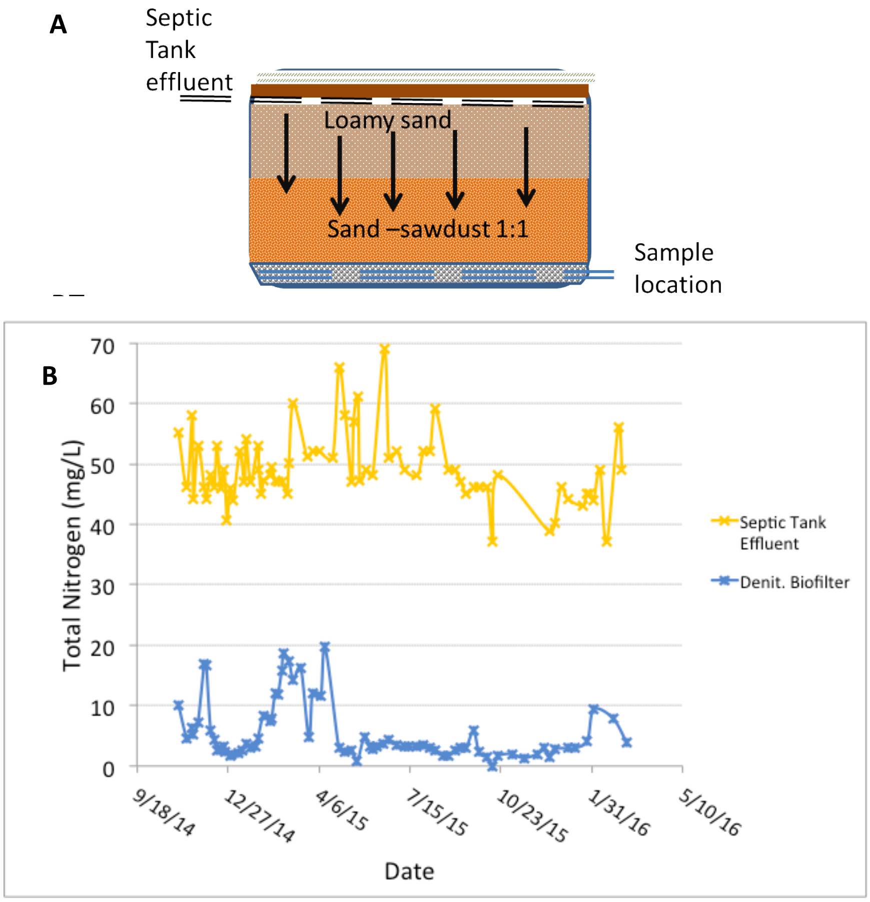

Figure 7. A) Configuration of pilot scale MASSTC in ground layered unsaturated system. B) Data plot showing TN concentrations over time compared to septic tank effluent. Note: no TN data were collected for the nitrification layer in this system.

Initial testing by MASSTC on these small scale and pilot systems indicated significant removal of TN, particularly in the saturated systems over time. Based on these prior successes, a full scale, 15 x 30 ft, NRB system was the next installed at MASSTC. The full scale system consisted of an 8-10” cover of top soil over a ultra-shallow low pressure distribution system, an 18” nitrifying sand layer overlying 18” of a 50:50 sand-sawdust layer. The sand-sawdust layer was contained in a poly-liner that was outfitted with a collection drain with stand pipe that maintained approximately 15” of saturation allowing for the top 3” of the mixed layer to be unsaturated (Figure 8). No final dispersal area was installed in this system. Hydraulic loading of wastewater to the system was 0.6 gpd/SF and was achieved via a low-pressure distribution system. Results, based on lysimeter sampling, indicated that a full 18” for nitrification layer was not necessary, and suggested that complete nitrification occurs within the upper 6” of the sand layer (Heufelder, pers. comm.). From an initial TN concentration in influent of approximately 50 mg/L, a mean of 8 mg/L TN (median 4.5 mg/L) was achieved over an 11-month period. The experiments suggest there is a response of denitrification to temperature, initially showing only a 50% reduction right after installation in the winter, and then as temperatures increased TN concentrations decreased significantly. It should be noted that this could be a function of timing of the install, which took place just before winter began. Thus, the lower TN removal during this first winter could be part of the "startup" phase, when the microbes responsible for denitrification may not have been fully established. Nonetheless, this system indicated that TN decreases in cold weather to a maximum of about 10 mg/L, and thus denitrification still occurred at cold temperatures, and subsequent winters may have more efficient TN removal as the microbial communities become more established.

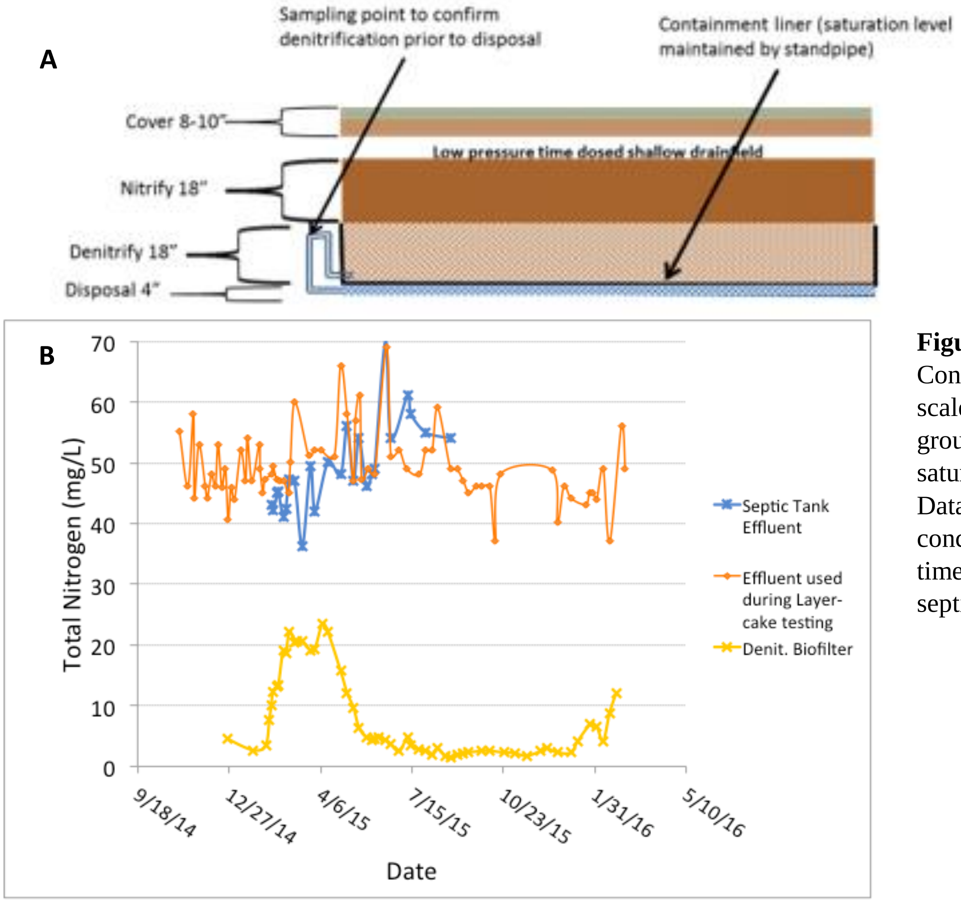

Figure 8. A) Configuration of large scale MASSTC in ground layered saturated system. B) Data plot showing TN concentrations over time compared to septic tank effluent.

The MASSTC tested another large scale, NRB consisting of a loamy sand layer overlying a silty sand+20% sawdust layer (Figure 9). Importantly, no liner was used, thus making this system free draining through the soil. Again, starting at a TN concentration of approximately 50 mg/L, effluent concentrations were a mean of 4.9 mg/L TN (median 4.1 mg/L) after a 6-month period. The highest concentrations measured, around 10 mg/L, occurred during the coldest part of the experiment (Figure 8B).

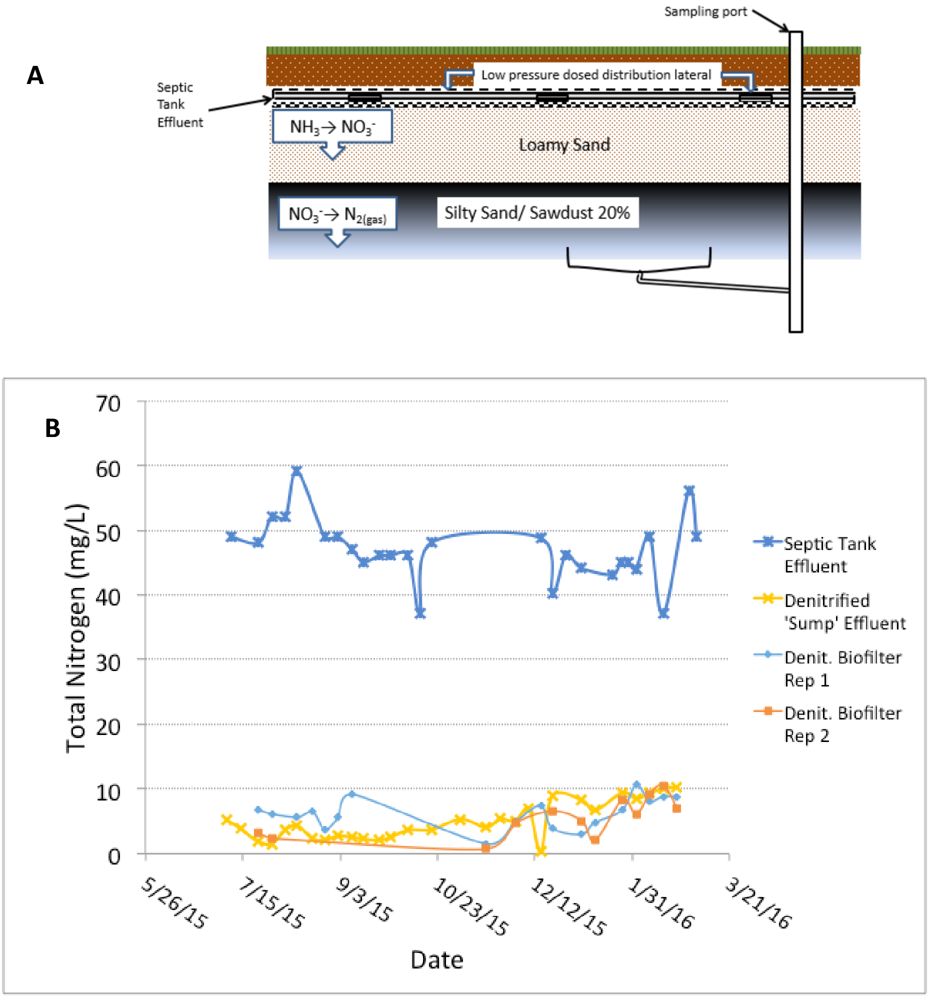

Figure 9. A) Configuration of large scale MASSTC NRBU system with silt-sawdust layer. B) TN concentrations in influent and effluent over time. Silt sump TN, Silt Port 1 TN, and Silt Port 2 TN are total nitrogen concentrations at various locations in the system after denitrification has occurred.

A final NRB system at MASSTC to report on was installed in December, 2015. This system consisted of a 6-8” cover layer, an 18” nitrification layer with 10% of loamy soil (i.e., 5-10% pass a 200 sieve), for improved nitrification, and an 18” denitrification layer consisting of a loamy sand/sawdust mixture (50:50; Figure 10). Although preliminary, results indicate greater than 50% reductions in TN near the start in cold weather (Figure 10). Based on past results from these systems, it is expected that effluent nitrogen concentrations will drop significantly through the spring, summer, and fall and as the system becomes established.

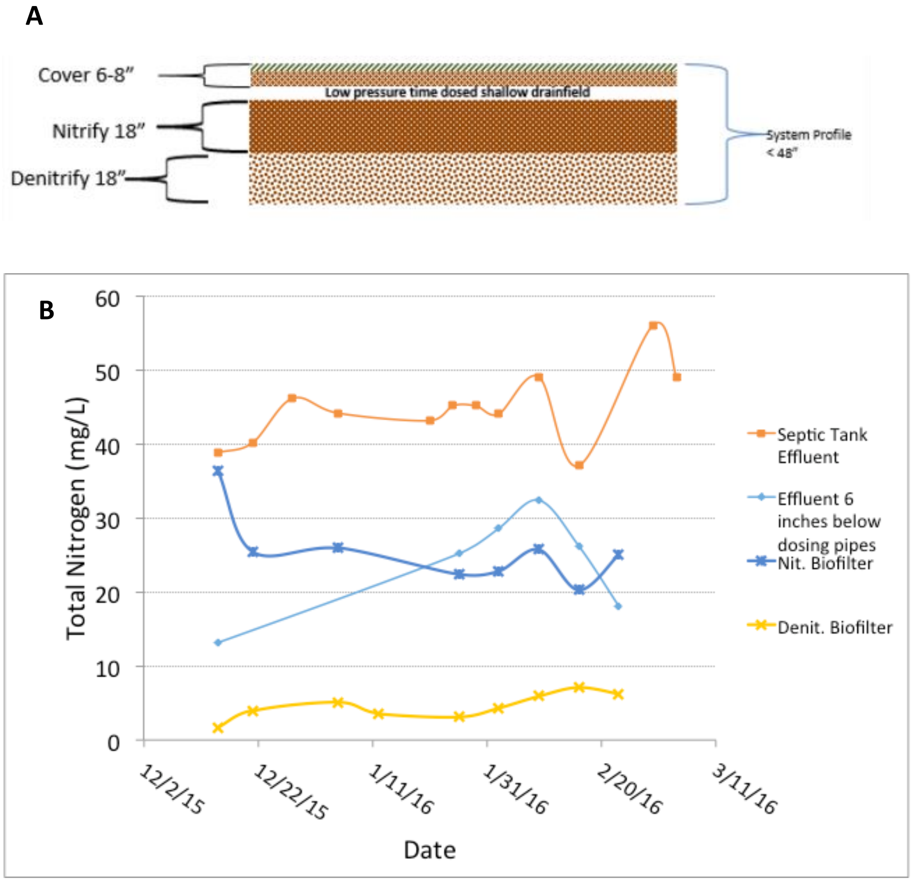

Figure 10. A) Configuration of large scale MASSTC saturated system with 10% fines added for better denitrification. B) TN concentrations over time at two depths in the nitrification layer and the bottom of the denitrification biofilter, compared to septic tank effluent. Note that nearly complete nitrification occurs within six inches beneath the dosing system.

CCWT results from sampling current installations at MASSTC:

A review of the relevant studies and investigations to date at both FOSNRS and MASSTC suggest that NRBs with adequate zones for nitrification and denitrification are highly efficient at removing nitrogen (approximately 90% TN removal). In particular, initial data suggests that prerequisite nitrification can be achieved in a relatively shallow soil profile and denitrification and reduction of TN to less than 10 mg/L is always achieved using a lignocellulose as a final step. Finally, microbial activities in these systems efficiently remove nearly all pharmaceuticals, personal care products, and other organic contaminants.

Recognizing the promise of NRBs for Suffolk County, CCWT is investigating several of the pilot stage NRBs currently installed at the MASSTC. Currently, the CCWT houses an array of geochemical and microbiological analytical equipment that provide the ability to measure or detect the follow analytes:

Nutrients:	TN, NO_3^-, NO_2^-, NH_4^+, N_2O, NO, N_2, PO_4^{3-}, Total P, DON, PON, and DOC
N Processes	incubations and analysis of N_2, NO, and N_2O transformation rates
Field Geochemistry	Temperature, pH, BOD, Alkalinity, DO, TSS, and Turbidity
Inorganic Chemistry	major anions: F, Cl, Br, and SO_4^{2-} major cations: Al, Ba, Ca, K, Mg, Mn, Na, Si, and Sr trace metals: Cu, Fe, Mn, Cd, Pb, Hg, As
Pharmaceuticals & Personal Care Products (PCPs)	Acetaminophen, Nicotine, Cotinine, Paraxanthine, DEET, Caffeine, Acesulfame K, Ibuprofen, Chlofibric Acid, Primidone, Bisphenol A, Naproxen, Carbamezapine, Salbutamol (Albuterol), Gemfibrozil, Cimetidine, Sulfamethoxazole, Ketoprofen, Diphenhydramine, Propranolol, Atenolol, Metoprolol, TCEP, Trimethoprim, Diclofenac, Warfarin, Fluoxetine, Ranitidine, Furosemide, Ciprofloxacin, Nifedipine, Fenofibrate, Amoxicillin, Diltiazem, Atorvastatin, Azithromycin, Furosemide, Estrone, β-Estradiol, 17α-Ethynylestradiol, and Nonylphenol
Microbial Diversity & Function	Total and Fecal Coliform, Enterococci, DNA, RNA and functional gene analyses utilizing state of the art metagenomics, metatranscriptomics, PCR and qPCR
Microsensors	NO_3^-, O_2

Both the large-scale saturated and unsaturated systems described above were sampled for a suite of geochemical and microbiological processes and parameters. Some results from this sampling are presented in Figure 11. Total nitrogen measured by CCWT has been consistent with the results reported in previous studies. During measurements made in January 2016, nitrogen conversion and removal performance were slightly different between the saturated and unsaturated systems. Results indicate that the total nitrogen (TN) in the influent stream consisted of dissolved organic nitrogen (DON 61.4 %), ammonia nitrogen (38.4 %), and nitrate (0.1%). These nitrogen species were significantly altered at the bottom of the nitrification layer. This system had multiple lysimeters (collection pans) installed at various depths (one at 12” within the nitrification layer, one at 18” at the transition between the nitrification and denitrification layers, and one beneath the denitrification layer). In the saturated system, ~ 60% of the TN was removed in the nitrification layer by a depth of 12 inches. The major forms of nitrogen species exiting the nitrification layer were ammonium (9.0 mg/L), and nitrate (7.0 mg/L). Total nitrogen (TN) concentrations of 4.0 mg/L were achieved in the final discharge of the saturated configuration. In the unsaturated, silt system, progressive nitrogen removal was observed as depth increased. The nitrification layer removed ~ 31 % of total nitrogen, with nitrate (22 mg/L) as the main end product. Total nitrogen (TN) concentrations of 8.5 mg/L were achieved in the final discharge of the unsaturated, silt configuration. These results demonstrate MASSTC’s passive NRBs are highly efficient at removing N (total efficiency of the saturated system was 90% and of the unsaturated, silt system was 79%), even in the winter. The data also show the systems are complex and the component layers do not – at least at low temperatures – completely separate conveniently into nitrification and denitrification zones. Instead, the nitrification layer appears to include micro-zones where both nitrification and denitrification may occur, a finding that may permit these systems to be refined further.

NRB (saturated denitrification layer)						
units: mg L^{-1} except (+/- SD)	**TDN**	**DON**	**NH_4^+**	**NO_3^-**	**N_2**	**N loss**
Influent	**40.4** **(+/- 0.3)**	**24.8**	**15.5** **(+/- 0.9)**	**0.02** **(+/- 0.3)**	**18.7**	
Nitrification Layer	**15.9**	**0.2**	**8.6**	**7.2**	**18.6**	**24.4**
Effluent captured in liner	**4.0** **(+/- 0.3)**	**b.d.***	**1.5** **(+/- 0.2)**	**2.7** **(+/- 0.4)**	**19.2**	**36.4**
					Total N loss %	**90**
NRB (unsaturated denitrification layer)						
units: mg L^{-1} except (+/- SD)	**TDN**	**DON**	**NH_4^+**	**NO_3^-**	**N_2**	**N loss**
Influent	**40.4** **(+/- 0.3)**	**24.8**	**15.5** **(+/- 0.9)**	**0.2** **(+/- 0.3)**	**17.6**	
Nitrification Layer	**28.0**	**6.0**	**b.d.**	**22.0**	**17.5**	**12.4**
Effluent captured in liner	**8.5** **(+/- 0.4)**	**0.1**	**b.d.**	**8.4** **(+/- 0.3)**	**17.8**	**31.9**
					Total N loss %	**79**

***b.d. = below detection limit measurements of N2 & nitrification layer were not triplicate**

Figure 11. Data collected from full scale saturated and unsaturated systems at MASSTC. Note: The data shown are averages of triplicate samples.

Advancing the understanding of NRBs: Measurements of dissolved N_2 and microbial diversity

One of the objectives of the CCWT is to measure dissolved N_2 in septic systems in order to elucidate nitrogen transformation pathways, as well as points of maximum N_2 production resulting from denitrification, thereby allowing questions of system design to be addressed and refined. The CCWT currently operates a Membrane Inlet Mass Spectrometer (MiMS) (Kana et al., 1994), which measures dissolved gases including N_2, O_2 and CH_4. Results, while preliminary, suggest that near-saturation of N_2 occurs in each layer. This near-saturation of N_2 confirms that the microbiological and geochemical conditions within the NRBs are highly conducive for denitrification. In addition, CCWT is in the process of using next generation, high throughput gene sequencing approaches to bring a unique understanding of the microbial communities present in NRBs that are responsible for nitrogen transformations and removal. Combined with dissolved N_2 measurements, this will provide unparalleled insight into the functioning of NRBs that should permit refinement and improvement in their operation and efficiency.

NRB Designs for Long Island

Based on these and other promising data, the CCWT is actively developing NRB designs to pilot on Long Island. To synthesize previous work and optimize future system design, the CCWT recently hosted a “design charrette” that included experts who designed the Florida and Massachusetts systems as well as individuals with significant experience in designing various types of standard soil treatment units, along with CCWT team members: Damann Anderson, P.E., Hazen and Sawyer; George Heufelder, Barnstable County Department of Health and Environment; David Potts, GeoMatrix LLC; George Loomis, University of Rhode Island; Dr. Jose Amador, University of Rhode Island; Glynis Berry, AIA, Peconic Green Growth; Christopher Clapp, The Nature Conservancy; Chris Lubicich, P.E., Suffolk County Department of Health Services; Justin Jobin, Suffolk County Department of Health Services; Dorian Dale, Suffolk County; and Carrie Meek-Gallagher, NYSDEC. From the CCWT at Stony Brook: Dr. Christopher Gobler; Dr. Harold Walker; Jennifer Garvey; Dr. Roy Price; Dr. Xinwei Mao; and Dr. Stuart Waugh.

Incorporating the most successful design configurations from MASSTC and FOSNRS, the following designs were selected for further testing as viable options for Long Island. These designs will be installed at MASSTC in 2016. Importantly, these systems will be constructed using materials native and easily obtainable in Suffolk County, allowing CCWT to verify the transferability of data from MASSTC systems to Long Island: Common concrete sand (C33), along with a more fine-grained fraction, available from several mining areas across Suffolk County; as well as wood chip material abundantly available from many yard waste transfer stations across the County. The wood from these transfer stations will be chipped to <1/4 inches, thus mimicking the grain sizes commonly used at MASSTC and FOSNRS. Additionally, CCWT is collaborating with Suffolk County to install a series of NRB systems locally as part of the Department of Health Services pilot program for innovative alternative onsite wastewater treatment.

1) A Lined Nitrification/Denitrification Biofilter

This system is designed to mimic the most successful designs to date, which can be described as a saturated NRB. The first configuration consists of a 6-8” soil cover, followed by a 12-18” nitrifying sand layer, and then a 12-18” sand and sawdust layer (Figure 12A). The system will be lined, which maintains saturation conditions and allows effluent to be directed to a dispersal system. The benefits of this configuration include: i) the well-lined bottom provides a more controllable system that increases the accessibility for sampling and monitoring; ii) aside from a single dosing pump, the processes are driven by gravity and capillary forces, thus reducing energy required for system operation; iii) a complete anoxic reaction zone can be obtained for extensive denitrification, iv) the saturated nature of the sand and sawdust layer should minimize any oxidation and degradation of the wood source over time. An alternative configuration is presented in Figure 12B. This configuration is also a lined, nitrification/denitrification system but the denitrification step is designed as an upflow. The additional benefit of this configuration is the up-flow mode in the denitrification layer requires no underdrain for effluent collection. The effluent is discharged through overflow of the system.

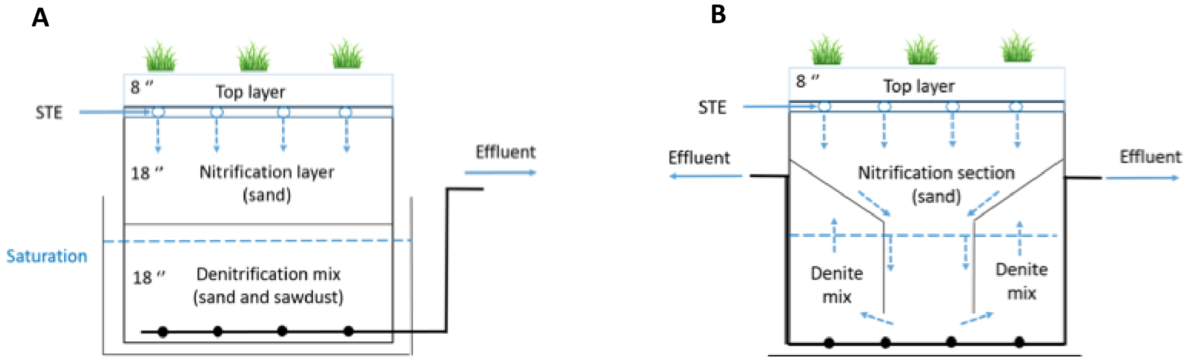

Figure 12. Lined Nitrification/Denitrification Biofilter. A) Configuration designed for removal of denitrified effluent through bottom drain. B) Configuration designed for gravity flow and overflow of denitrified effluent via hydrologic pressure.

2) Sequence Nitrification/Denitrification Biofilter

One concern expressed to date regarding NRB has been the life of the lignocellulose (wood) as a carbon source within the denitrifying layer. Calculations by CCWT have indicated that, theoretically, these wood

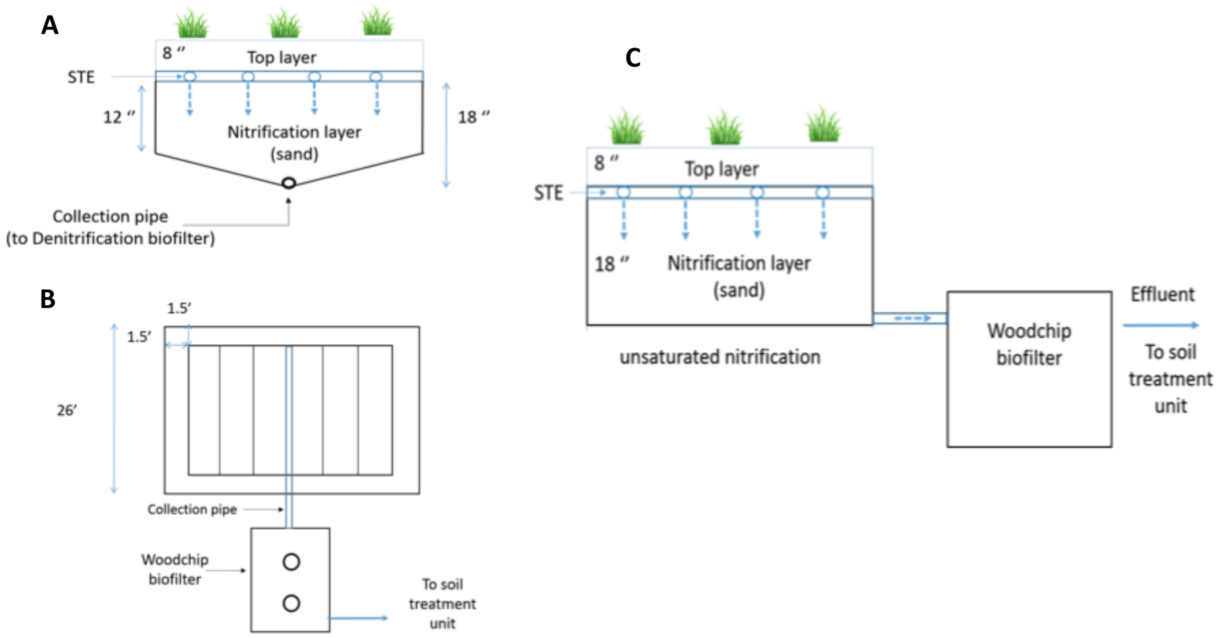

Figure 13. Sequence Nitrification/Denitrification Biofilter. A) Front view of nitrification layer configuration. B) Plan view. C) Longitudinal cross section view.

sources should persist for many decades (more than 100 years). Still, given that no NRB has been in existence for more than a decade, definitively knowing the life of wood sources in these systems is an open question. The final design described here addresses this by coupling the sand layer of NRB with an upflow ‘wood chip biofilter in a tank’ that can be refilled as needed over the life of the system. This system will consist of a 12-18” layer of nitrifying sand (Figure 13A-C), which funnels the nitrified effluent into a collection pipe. This nitrified effluent is then gravity-fed or dosed with a low pressure pump into the bottom of a tank filled with saturated woodchips, with flow up through the biofilter to an effluent dispersal system. This tank will have a lid at the ground surface and thus can be accessed for sampling as well as for replacement of woodchips as needed.

Conclusions & Future Steps

Long Island faces significant challenges with respect to the contamination of its groundwater by nitrogen and other pollutants that emanate from household wastewater treatment systems. The NYS Center for Clean Water Technology was established with the goal of developing and commercializing technology that will be efficient, reliable, and affordable at removing nitrogen and other contaminants from onsite wastewater. The CCWT has identified NRBs as a technology potentially capable of meeting this goal, and is actively developing the next generation of NRBs with the objective of identifying the optimal configurations for Long Island. This work includes investigation of the materials (e.g., types of sawdust or woodchips in various combinations with different sands) that will afford the maximum system efficiency, affordability, and fit for the region. Additionally, the analysis of local pilot installations will enable continued assessment of other key questions including cold-weather performance (especially with seasonal or intermittent flows), clogging potential, durability of the system and components, and long-term performance levels (e.g., is there an ionic adsorption component in early system operation that is reduced over time).

In the near term, the CCWT is scheduled to install and assess multiple new NRB configurations at the Massachusetts Alternative Septic System Testing Center. A series of NRB pilot installations on Long Island are also planned in collaboration with the Suffolk County Department of Health Services to evaluate system performance in a range of dynamic local conditions.

However, while NRBs are potentially one economically viable, high-performance option for future onsite wastewater treatment on Long Island, other solutions will be needed as the system footprint is larger than conventional systems and unsuitable for some residential lots. To this end, the CCWT continues to work in collaboration with the Suffolk County Department of Health Services towards the development and commercialization of additional wastewater treatment technologies to retrofit or replace its hundreds of thousands of aging septic systems.

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