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BEST PRACTICES FOR DEEP ROW ENTRENCHMENT (DRE) OF BIOSOLIDS USING HYBRID POPLAR TREES

Abstract

Deep row entrenchment (DRE) is a biosolids beneficial reuse system suited to strip mine reclamation that uses a one-time application of biosolids in wide and shallow trenches covered with overburden, and planted with hybrid poplar cuttings. The trees utilize the nitrogen and other nutrients over a five to seven year rotation and produce many environmental benefits (reduced erosion, improved water quality, woody biomass, and wildlife habitat). DRE solves many of the problems associated with surface application but it is not well understood by regulators, environmentalists, and others. This publication brings together the science and operational experience for DRE for the purpose of encouraging its proper application.

Images on right: Abandoned gravel mine with eroded drainage channels in southern Maryland prior to reclamation and deep row entrenchment (top) and same site after deep row entrenchment and growth of hybrid poplar trees (bottom).

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Why This Publication?

Deep row entrenchment (DRE) is a biosolids beneficial reuse system suited to strip mine reclamation that uses a one-time application of biosolids in wide and shallow trenches that are covered with overburden, and planted with hybrid poplar cuttings (Figure 1). The trees utilize the nitrogen and other nutrients over a five- to seven-year rotation and produce many environmental benefits: reduced erosion, improved water quality, woody biomass, and wildlife habitat. In combination with an appropriate nutrient management plan and a plant and soil testing program, DRE can be used repeatedly as an income generator. Developed by ERCO, Inc., DRE was operated successfully on an old gravel mine spoil in Maryland from 1982 to 2013. Seven years of intensive water quality research by the University of Maryland on a 3-acre site within the operational DRE area found that soil water nitrate content was essentially zero for the first three years and increased to between 1 and 10 mg/l, which is similar to that of a well-managed cornfield. While Maryland has not encouraged the technique, it is being used on coal mine spoils in Pennsylvania, Ohio, and in other applications. DRE solves many of the pollution and odor problems associated with conventional surface application of biosolids, but DRE is not well understood by regulators, environmentalists, and others.

DRE provides a cost-effective method to reclaim old coal mine spoils created before the Surface Mining Control and Reclamation Act of 1977 (SMCRA), which requires re-grading and stabilizing the surface with grass or other vegetation. Old coal mine spoils can impair water quality through erosion and acid mine drainage, but DRE will build soil fertility, resulting in the creation of sustainable forests and wildlife habitat that will keep water on site and improve water quality of surrounding areas.

The authors were involved with the initial research by the University of Maryland and, after visiting with various DRE operations, attempt to bring together the state of science and operational knowledge to advance wider commercial adoption of the technique.

What are Biosolids?

Biosolids are treated sewage sludge meeting the U.S. Environmental Protection Agency (EPA) pollutant and pathogen requirements for land application and surface disposal. They usually contain from 1-4% nitrogen and 60-85% water, and are a valuable source of fertilizer for agriculture and forest crops.

The Clean Water Act (CWA) of 1972 set a framework for biosolids regulations and in 1973 brought the management of residuals from waste water treatment processes under the federal regulation known as *Part 503 Standards for the Use and Disposal of Sewage Sludge*. The regulation establishes standards, which consist of general requirements, pollutant limits, management practices, and operational standards, for the final use or disposal of sewage sludge generated during the treatment of domestic sewage in a treatment works. Standards are included for sewage sludge applied to the land, placed on a surface disposal site, or fired in a sewage sludge incinerator. Also included are pathogen and alternative vector attraction reduction requirements for sewage sludge applied to the land or placed on a surface disposal site.

Today's biosolids are not the biosolids of 1970's and 1980's. Through the Source Reduction Act and the Pollution Prevention Act, a great many of the issues with biosolids have been eliminated or reduced to levels that are no longer a concern. Pollution prevention is reducing or eliminating waste at the source by modifying production processes, promoting the use of nontoxic or less toxic substances, implementing conservation techniques, and reusing materials rather than putting them into the waste stream. Metals levels in biosolids have been reduced by orders of magnitude through pollution prevention and source reduction. Other contaminant levels that were a concern 35-50 years ago have been similarly reduced.

Biosolids produced by wastewater treatment plants (WWTPs) can be classified as either Class A or Class B, based on the concentrations of remaining pathogens.

- **Class A Biosolids** have been treated (usually through addition of lime, heat from composting, or direct heat) to reduce fecal coliform levels below a safe standard. After meeting the treatment standard Class A biosolids can be applied to land with no restrictions, and is a marketable "product" that can be distributed to the public for landscapes, gardens, and park uses.
- **High Quality Biosolids** are class A biosolids that also meet vector attraction standards.
- **Class B Biosolids** have undergone some basic pathogen reduction at the waste water treatment

plant, but still have pathogen levels that can be dangerous to humans. Treatment frequently involves anaerobic digestion followed by some dewatering. In many cases lime is added to the biosolids. Class B biosolids can be applied on farm crops that are not eaten by humans, such as feed corn, soybeans, and other crops fed to animals.

Both Class A and Class B biosolids must have heavy metal concentrations that are below certain standards.

Biosolids Utilization

The challenge with biosolids is to find utilization methods that capture the nutrient and soil enhancement benefit, commonly referred to as beneficial reuse. Landfilling of biosolids is disposal and not desirable not only because the nutrient value wasted, but because landfill capacity is limited and it is increasingly hard to site new landfills. Additionally, landfilling biosolids results in methane release from the landfill. Methane is a significant greenhouse gas. Incineration to produce energy has become less desirable to the public because of concerns with air quality.

Beneficial reuse options include surface application of Class B biosolids to agricultural land and marginal lands; the distribution and marketing of Class A biosolids; production, distribution, and marketing of High Quality Class A biosolids; and DRE. Figure 1 shows the utilization of biosolids in Maryland in 2014. Only 6% of biosolids are used for agricultural application in Maryland and 7% of Maryland's biosolids are distributed and marketed as Class A biosolids. Landfilling is 4% and incineration is incidental. What is important is that 60% of biosolids are hauled out of state and applied to agricultural land in Virginia and Pennsylvania, making about 66% of total biosolids applied to agricultural land.

There is growing interest in increasing the production of Class A biosolids that can be distributed and marketed. Producing Class A biosolids requires more expense and it is questionable how much more can be marketed in regional markets above and beyond what is already produced. Land application of Class B biosolids produced from municipal waste water treatment plants has become the preferred option for large-scale nutrient recycling when compared to landfilling and incineration because it utilizes the nutrient value of biosolids for growing crops and forests.

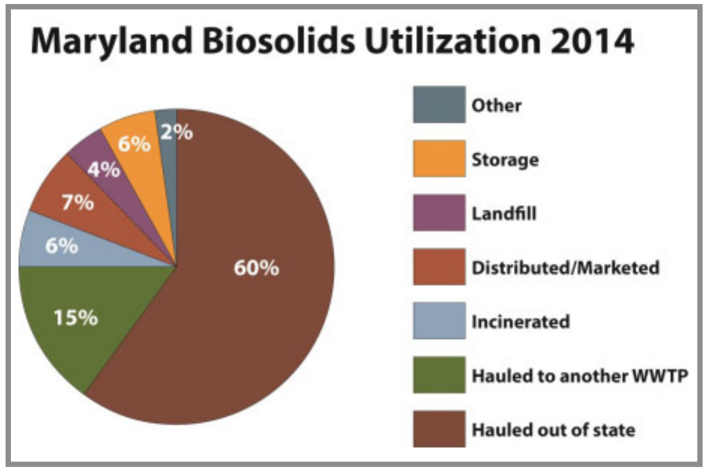

Figure 1. Maryland biosolid utilization for 2014. Note 60% is hauled out of state. Data provided by MDE Land Management division (2015).

Trends in Biosolids Utilization

The trends in biosolids utilization from 2010-2014 (Figure 2) indicates that agricultural application in Maryland has declined and there has been a corresponding increase in the percentage hauled out of state. From 2010-2014, in-state agricultural application fell from 24% to 8% and biosolids hauled out of state increased a similar amount from 48% to 66%.

In Maryland, it has become increasingly difficult to apply Class B biosolids on agricultural land due to accelerating land prices, the disappearance of farm land, social issues surrounding odors, and perhaps most important, the enactment of phosphorous (P)-based nutrient management regulations on soils that are classified as having high P levels prior to surface application of biosolids. Phosphorus-based regulations set application rates based on P instead of nitrogen (N), which typically results in lower application rates per acre, the need for supplementary N application, and challenges the cost-effectiveness of surface application. Because 60% of Maryland biosolids production (Figure 1) goes out of state, Maryland is dependent on the biosolids application policies of adjacent states accepting out-of-state biosolids. Hence, it would prudent of Maryland to find new innovative methods for beneficial reuse of biosolids. As other states start to implement P-based nutrient management regulations, Maryland could see the out-of-state haul option greatly diminished. DRE provides an opportunity to fill any resulting utilization gap.

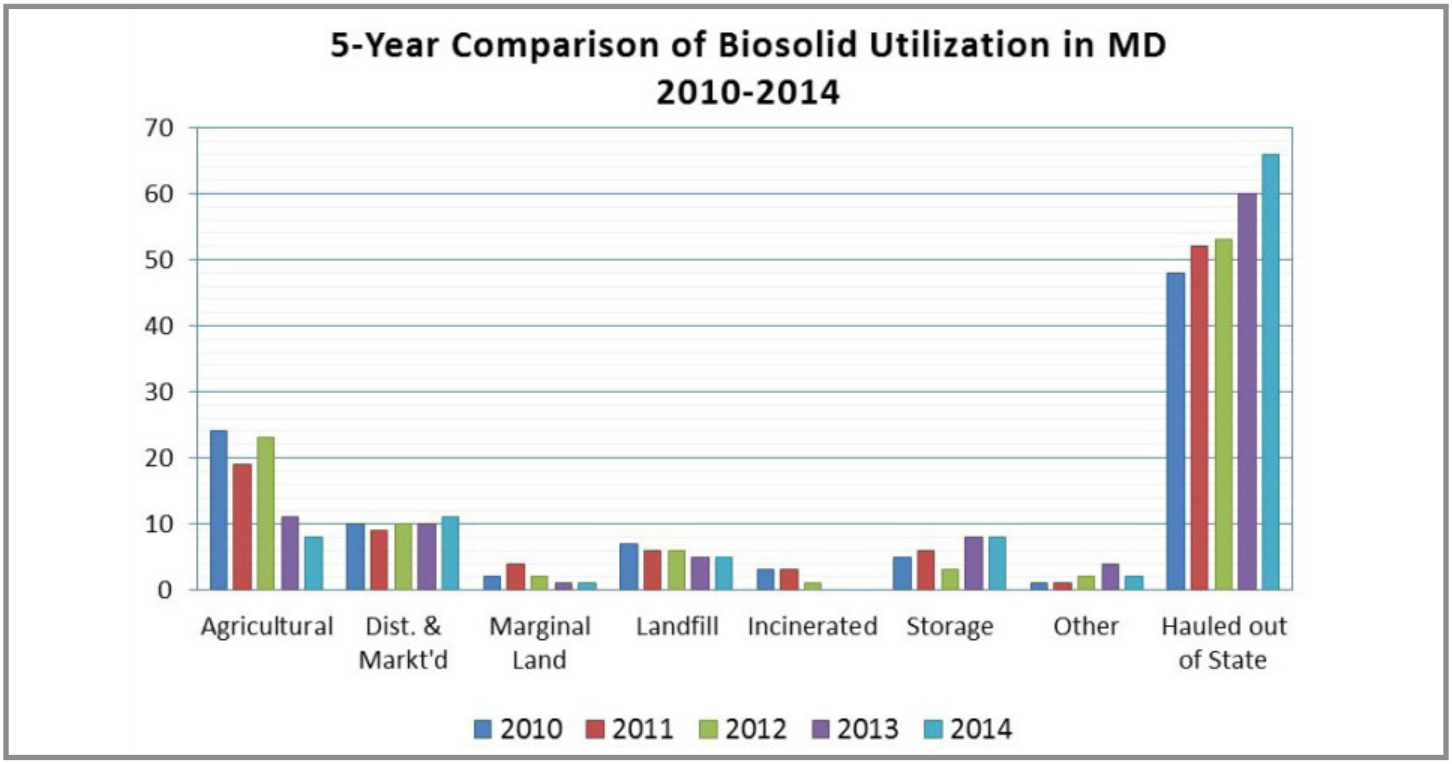

Figure 2. Changes in biosolids utilization from 2010-2014. Note the decrease in agricultural application and corresponding increase in biosolids hauled out of state for agricultural application.

Deep Row Entrenchment (DRE)

DRE is a unique biosolids beneficial reuse system that combines short-rotation hybrid poplar production and the deep row application of biosolids to reclaim mine spoils, other drastically disturbed soils, or marginal soils, solving the problems associated with surface application of biosolids while providing environmental benefits and a positive cash flow. DRE is not subsidized but actually produces business income.

The concept of DRE is not new, but the addition of deep-rooted, nutrient-demanding trees, such as hybrid poplar, to utilize the nutrients is a new improvement. After the passage of the CWA of 1973, WWTPs in the Washington DC area were looking for new biosolids utilization options, and experimented with burying biosolids in deep trenches. A number of researchers at the time determined how the biosolids changed over time in the trenches. However, they only planted shallow rooted annual crops that were not able to utilize the nutrients buried in the trenches. While the buried biosolids eliminated odor problems and created an anaerobic environment that stalled nitrogen mineralization for a few years, nitrate leached from the deep rows as time progressed. The lack of deep-rooted vegetation to utilize the nitrogen for plant growth released from the biosolids was one of two main causes of nitrogen loss. The other factor was the soil type.

The site was mined for gravel in the 1960's and 70's and what was left in 1983 was biologically sterile sand and gravel overburden, with a clay layer below, that was heavily eroded and needed reclamation (Figure 3). ERCO, Inc. wanted to use the marginal land to produce tree crops using biosolids as the nutrient base.

Gravel mounds initially covered the ERCO property and it was underlain by 30 to 90 feet of clay. The mining operation removed the sand and gravel at the surface (approximately 20' to 30' thick) and left the heavier deposits exposed to weathering (Figure 4). The underlying marine clay layer is a deep restricting clay layer that minimizes vertical leaching while tree roots colonize the site and utilize the nutrients. This clay maintains an anaerobic environment in the DRE trench which inhibits nitrogen mineralization. The average thickness of clay layers in Southern Maryland is 40 feet. The layers consist of clay, sandy clays, and silty clays.

A private consulting company developed a nitrogen budget for DRE using hybrid poplar trees that balanced the expected availability of nitrogen in the biosolids pack over time with uptake of nitrogen by the trees. It

Figure 3. Heavily eroded gravel spoil prior to reclamation using DRE was having detrimental effect on water quality. Note the lack of any vegetation growth.

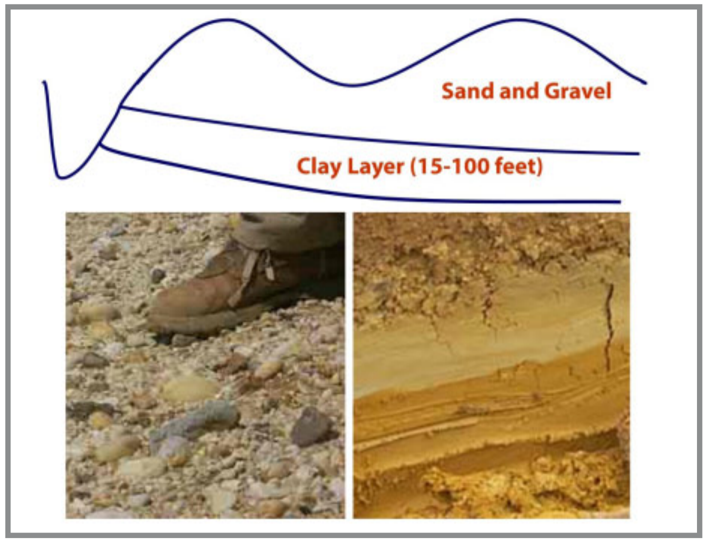

Figure 4. Diagram and associated pictures that show the solid clay layer that underlies the gravel deposits removed in the mining operation.

provided the research base to obtain a research permit from the Maryland Department of Environment (MDE).

DRE involved a biosolids application of 171-295 dry tons per acre in deep rows or trenches. The deep rows were excavated using a backhoe to 36” deep by 42” wide and located eight-feet apart on center. The deep row was partially filled with biosolids, covered with about 16-20” of overburden, and planted with hybrid poplar cuttings in the spring.

Prior to a truck arriving on site, a trench was excavated using a custom-made bucket that was 42 inches wide (Figure 5). The trench was dug to a depth of 36 inches. When the truck arrived, biosolids were emptied immediately adjacent to the trench. In a matter of one or two hours, the biosolids were pushed into the trench with a bulldozer to the appropriate depth and covered with overburden. The resulting field resembled a moonscape of rows of spoil mounded to approximately two feet high. When the entire 10-acre section was trenched and filled, a bulldozer was used to smooth the surface and prepare it for planting.

Preparing the site for planting is critical to assure successful survival and growth after spring planting (Figure 6). The heavy clay soil overburden at the ERCO site quickly settled after biosolids were applied for DRE. Operational experience found that a bulldozer with subsoiling bar was needed to loosen the compacted soil on 10-foot centers so that roots produced by the cuttings could penetrate the overburden and access the biosolids pack. One study found that mortality after one year increased from 1.7% for cuttings planted with subsoiling, to 14.2% for cuttings planted without subsoiling. The absence of rock and pliable overburden was well-suited to subsoiling on gravel spoils at ERCO, but would not be realistic on coal mine spoils with large rock components. After six to eight years the nitrogen in the biosolids is consumed for tree growth, leaving behind a fairly stable “peat-like” material. Each year the N in the biosolids pack and foliar N levels were monitored and when 70% of the N in the biosolids were mineralized and foliar N levels dropped below 3.5%, the trees can be harvested, the site retrenched, and biosolids reapplied. The ERCO site has some areas that received three applications and the overburden in these areas starts to show some mixing of organic matter with the more sterile material (Figure 7). DRE creates soil material that is stable and adds organic matter to an otherwise sterile overburden. It is hoped that it will continue to build a soil base that can support a native forest in the future.

The success of DRE using hybrid poplar trees is dependent upon one or a combination of two factors: the presence of a restrictive soil in the overburden that minimizes downward movement of nitrogen until tree roots colonize the site and utilize the mineralized nutrients; and/or, rapid root formation by hybrid poplar which provides oxygen to the biosolids, and increases mineralization and nutrient uptake.

Figure 5. Pictures show progression of DRE. A trench is dug with a backhoe and biosolids deposited next to the deep row are pushed into the deep row and quickly covered. The site is graded and ready for planting.

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Essential Basics of the DRE System

The DRE technique utilizing hybrid poplar trees was developed in 1983 by an innovative Maryland based company, ERCO, Inc., on a 93-acre gravel mine spoil in Prince George's County, Maryland. The site is within 25 miles of several large municipal wastewater treatment plants.

Essential Geology

The DRE system is on a sand and gravel mine spoil. The surface has nothing that we would normally consider a soil. An impeding layer (five to 70 feet or more thick) is an essential characteristic of a suitable site for DRE. Descriptions of geology at the ERCO site were derived from Wilson and Fleck (1990) and, to a lesser extent, Tompkins (1983). The following describes the deeper deposit first and concludes with the surface deposit that was removed in the mining operations.

The lower formation is the Marlboro Clay, a confining unit of dense, reddish silty clay between 15 and 30 feet in thickness. The lower Eocene Nanjemoy Formation overlies the Marlboro Clay, and predominantly consists of beds of dark green, fine to medium, glauconite-bearing sands in the upper part of the formation. The thickness of the Nanjemoy at Waldorf ranges from about 90 to 125 feet.

Overlying the Nanjemoy is the lower Miocene Calvert Formation. The Calvert is a light to medium, olive gray to olive green, micaceous, clayey silt. The thickness of the Calvert in the Waldorf area is about 90 to 100 feet. The formation is the basal unit of the Chesapeake Group and it represents deposition in a marine shelf environment.

The Calvert is overlain by the Pliocene Upland Deposits. The Upland Deposits consist of orange-tan, silty, fine to very course sands and gravels, and yellowish to orange, silty clays. The Upland Deposits range from 20 to 50 feet. thick and crop out throughout the Waldorf area. These materials are what was removed in the sand and gravel mining process. Hence, the ERCO site has very slight remnants of the Pliocene Upland Deposits over the Calvert clayey silt, over the Nanjemoy.

Figure 6. Bulldozer pulling subsoiling bar and 10' boom attached to mark planting grid (top left). Cuttings planted at intersection of 10' X 10' grid (top right). Young trees with and without control of competing vegetation (bottom left). Trees after seven years growth (bottom right).

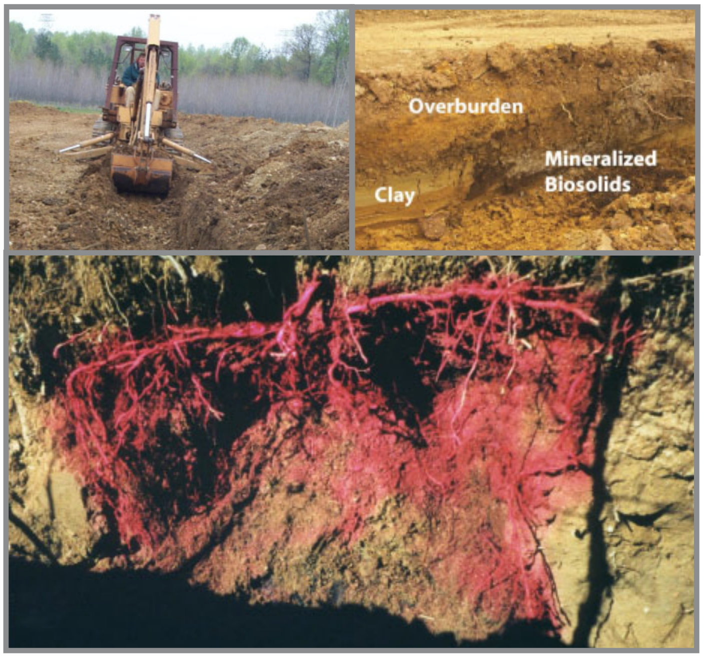

Figure 7. New trench passing through previous trenches at approximately 90° (top left). Crosscut of old trench showing mineralized biosolids residuals surrounded by clay and overburden (top right). Excavated painted tree roots show wrapping of roots around trenches to utilize nutrients (bottom).

The DRE system requires certain soil conditions and plant properties. Soils must restrict air flow and water flow. This enables the biosolids pack to remain anaerobic until the plant roots reach the trench The anaerobic conditions in the deep rows halts the mineralization of nitrogen until tree roots facilitate the uptake, creating a closed recycling system for nitrogen and minimizing problems with nitrate leaching. The soil should have some clay content. Ammonia in the biosolids begins to leave the biosolids pack, most likely by diffusion. Clay in the soil has a negative charge and attracts the ammonia ion, retarding ammonia migration away from the trench.

We suggest that the deep row technique may be appropriate for soils classified as clays; clay, clay loam, silty clay, silty clay loam (these soils contain 27% clay or more by textural analysis). It is possible that other soils such as sandy clay loams and loams may be appropriate, but additional research is necessary to make this conclusion.

The plant in the DRE system must have roots that can penetrate the soil and the plant must transport air to the roots. A year or so after planting, the roots of hybrid poplar start to surround the deep row and provide oxygen through the root tips, allowing the transformation of the organic N in the biosolids into nitrate which is quickly taken up by the trees to sustain growth. Poplar have a tissue structure called an *aerenchyma* which is a tissue structure which forms void spaces in the leaves, stems, and roots of some plants, allowing air to move into the root zone. Many wetland plants have *aerenchyma* but hybrid poplar also have it. The combination of soil properties and plant properties result in a kind of closed nitrogen recycling system that minimizes nitrate leaching to groundwater.

A concern of people not familiar with the details of DRE is a long trench that has biosolids in it and could build up a sufficient hydraulic head to break out of the soil and become a local seep. The trench has contiguous biosolids for 60-90 feet at most. Anytime biosolids are entrenched, soil is immediately filled over the biosolids. This results in a four to six foot section of the trench filled with only soil/spoil. Hence, the myth of a long contiguous trench filled with biosolids doesn't actually exist.

Why Do We Monitor?

Monitoring DRE land typically is for either **research** purposes or **regulatory** purposes. DRE is a topic that has only a small research effort behind it. The magnitude of the work is a limiting factor. Without heavy excavation equipment and trained operators, researchers cannot install monitoring systems on DRE land. That means the landowner that is doing the DRE work must be in favor of and contribute help to the monitoring project. When monitoring for research, we are interested in understanding one or more of the following phenomena:

- How nutrients move, both vertically and horizontally.
- How nutrients are transformed in the biosolids mass in the spoil.
- How the concentrations of nutrients (especially nitrogen) near the trench changes as distance from the trench increases.
- How the mass flow rate of water through the spoil and through the biosolids changes over time.

Some Basic Groundwater Terminology You Need to Know

- **Saturated**–Porous media is made up of mineral solids, water, and air. When all the pores between the mineral solids are filled with water (there is no air in the porous media) then the media is saturated.

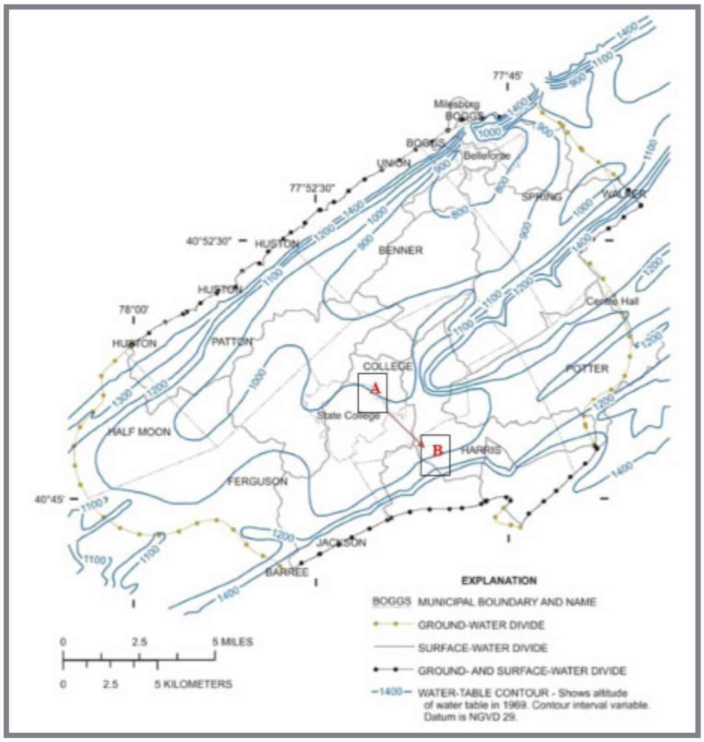

Figure 8. Potentiometric surface map of the Spring Creek Groundwater Basin ca 1969. (www.e-education.psu.edu)

- **Hydraulic head**–Water potential is made up of elevation, pneumatic pressure, water pressure, osmotic pressure, and thermal potential. If the media is saturated, there is no capillary effect on water pressure. If the temperature is fairly consistent throughout the porous media, then there is no thermal potential. Typically, there is no pneumatic (air) pressure imposed on ground water flow. That leaves the height of the column of water and the elevation. Together, those two elements make up hydraulic head.

- **Gradient**–Differences in hydraulic head cause water to move from one place to another. That is, *water flows from locations of high hydraulic head to locations of lower hydraulic head*. The gradient is the change in hydraulic head per length of flowpath. Maps of hydraulic head (Figure 8) can be used to determine the direction of groundwater flow on a regional basis.

  In Figure 8, the water flows along a gradient from the high hydraulic head (point A) to the lower hydraulic head (point B) . The gradient can be measured from these maps. This can be used, along with a few well tests, to make estimates of water flow. Water flow combined with concentration can be used to estimate constituent mass transport, the final goal of monitoring.

- **Vadose zone or unsaturated zone**–The vadose zone is the undersaturated portion of the subsurface that lies above the groundwater table; that is, between the land surface and the top of the capillary fringe, the position at which the groundwater (the water in the soil's pores) is at atmospheric pressure. Water in the vadose zone has a pressure head less than atmospheric pressure, and is retained by capillary action.

  In fine-grained soils, capillary action can cause the pores of the soil to be fully saturated above the water table at a pressure less than atmospheric. The vadose zone does not include the area that is still saturated water table, often referred to as the capillary fringe. It is of great importance in providing water and nutrients that are vital to the biosphere, and it is intensively used for the cultivation of plants, construction of buildings, and disposal of waste.

  The vadose zone is often the main factor controlling water movement from the land surface to the aquifer. Thus, it strongly affects the rate of aquifer recharge and is critical for the use and management of groundwater. Flow rates and chemical reactions in the vadose zone also control whether, where, and how fast contaminants enter groundwater supplies. DRE trenches are installed in the vadose zone and monitoring for the fate and transport of constituents in the biosoids is indicative of processes that occur in the vadose zone.

Tools for Measuring Water Quality

Lysimeters are devices that collect subsurface water samples for later analysis. There are two basic types of lysimeters: suction lysimeters and zero tension pan lysimeters.

- **Suction lysimeters** collect samples from unsaturated porous media. In order to function, suction lysimeters are embedded in saturated soil (mud). Suction is applied to the PVC cylinder and water passes from the soil through the porous cup at the bottom of the lysimeter and into the PVC cylinder, usually over 24 to 72 hours. Clearly, the samples are a snapshot in time. Additionally, lysimeter samples from below the DRE trench are worst-case scenario values. This is the primary

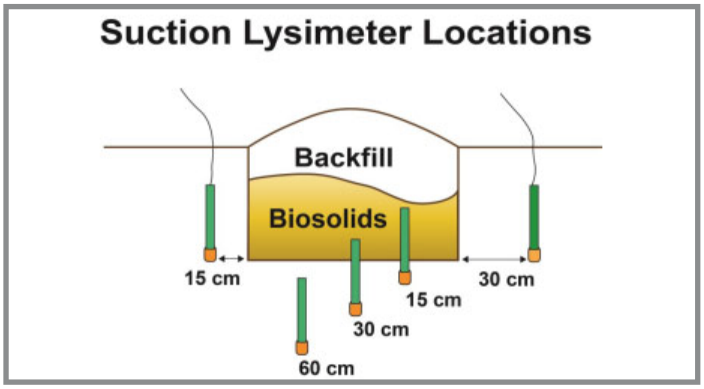

Figure 9. Schematic of suction lysimeter installation around a DRE trench illustrating a 3-lysimeter nest below the trench and a 2-lysimeter nest lateral to the bottom of the trench.

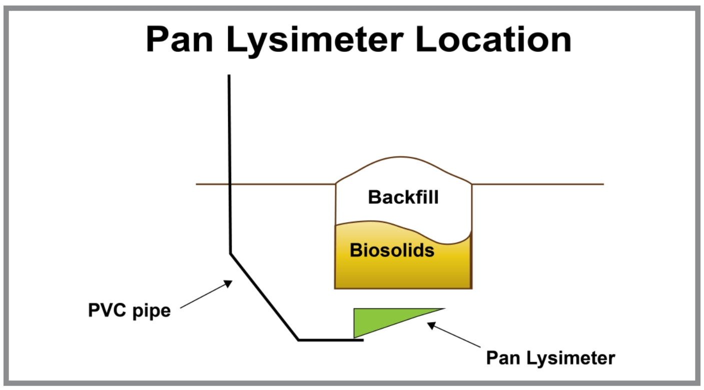

Figure 10. Schematic of zero tension or pan lysimeter installed beneath a DRE trench.

device for sampling soil water. By itself, a suction lysimeter can provide contaminant concentration, but not mass flow rate. For DRE studies, suction lysimeters are installed in a nest directly below the entrenched biosolids. A four-lysimeter nest might be 10, 20, 40, and 120 cm below the bottom of the DRE trench. Where lateral flow is also of interest, suction lysimeters can be used (Figure 9).

- **Zero tension or pan lysimeters** (Figure 10) are carefully placed at a particular depth below the soil surface. Saturated flow drains by gravity into the lysimeter and is removed by a tube to the surface. Zero tension lysimeters provide contaminant concentration and, at least to a limited degree, mass flow rate. For DRE studies, zero tension lysimeters are installed 20 cm below the bottom of the DRE trench.

The soil water that runs to a suction lysimeter moves through the porous media matrix and can take a long time to move. Water that moves to a pan lysimeter is gravity drainage and it moves through the path of least resistance. These are often preferential flow paths and water movement can be very rapid. The opportunity time for contaminants to move into the soil water is usually greater than the opportunity time for contaminants to move into preferential flow. Typically, contaminant concentration is higher in suction lysimeters than in zero tension lysimeters. However, zero tension lysimeters are difficult to install in coarse sand and gravel because of soil collapse while excavating a slot for the lysimeter. Lysimeters can be installed in loose granular porous media inside a container with a bottom that is buried in the ground. It is not impossible to install lysimeters in broken rock spoil, but it difficult to install them and it is difficult to obtain good results and verify the quality of the results.

Drain lines are just what the name implies. Corrugated Plastic Tube (CPT) is used to collect water and route it to an outlet where it can be sampled and, often, a tipping bucket flow meter can measure flow continuously. Lysimeters are essentially a point sample. CPT drain lines provide a linear sample area and the sample itself is an average value across the length of the tube. The tube is installed in sand that is put below, around, and above the tube. Water flowing in broken rock spoil will enter the sand and then enter the CPT. All flow is gravity flow but flow in broken rock spoil is not necessarily saturated, in the classical porous media flow meaning of the word. Flow in broken rock spoil has characteristics of open channel flow in small channels between the broken rock pieces. Just as saturated flow in porous media is water that moves easily and rapidly, relative to unsaturated porous media flow, flow in broken rock spoil moves easily and rapidly.

Wells are used to collect both water samples for constituent analysis and to measure hydraulic head. A well is viewed as a point source. In plan view, it may represent a point on a map of hydraulic heads (Figure 23) or a map of contaminant concentrations. Under saturated conditions, water flows from a higher hydraulic head to a lower hydraulic head. Wells collect water from porous media. If the media is saturated and the well screen is in a short section of well pipe, then the sample is considered to be a sample from a point in three-dimensional soil/spoil. A well with a long screened length (e.g. 90 feet) provides information about constituent presence, but may or may not provide information about concentration or mass flow. Long screens mask the influence and character of different

Figure 11. Excavating slot for pan lysimeter installation in granular porous media.

geologic formations that yield different constituents and different volumetric flow rates of water, masking actual concentration and mass flow information. Hence, interpretation of concentration data may require good geologic knowledge of the area.

Wells for water quality sampling are arranged, **at a bare minimum,** with at least one well up-gradient of the suspected source of the constituent of interest and two down-gradient of the suspected source of the constituent of interest. Lysimeter data are not necessarily well received by regulatory personnel while wells and well data are generally understood and accepted by regulators.

Installation of Water Quality Sampling Devices

First, no two mine spoils are identical in physical or chemical properties. Therefore, the hydraulic properties that characterize vertical flow into the spoil and through the spoil will be different at each and every site, as well as from point to point within a site. That being said, we look at similarities and design monitoring systems based on similar spoils. Sometimes we are successful and sometimes not. Sometimes, regulatory requirements will dictate the design of a monitoring system.

The tools used to measure water quality generally have to be installed in some form of mine spoil. All installations require excavation and/or drilling to put the water capture device where the water will pass through the suspected constituent source on its way to the capture device. The characteristics of the media influence the type of device and the installation procedure.

Installation in Granular Media

A pan lysimeter is a rectangular metal (usually stainless steel) pan that collects saturated flow from the surface. This flow is disproportionally macropore flow in well-developed soils. The procedure involves digging an access trench next to the location for the pan lysimeter and then excavating a slot, usually by hand, horizontally into the side wall of the trench (Figure 11) . The pan lysimeter is installed in the slot and is directly below the trench.

In broken rock spoil, the water flows in a manner that resembles open channel flow if the particle size distribution is coarse and can be preferential flow through porous media if the particle size distribution is finer.

A pan lysimeter installed into porous media spoil would be placed directly below the DRE trench with the intention of collecting preferential flow with the worst-case contaminant concentration. A typical pan lysimeter can hold two to 10 liters, depending on the dimensions of the lysimeter. If the lysimeter is sampled frequently enough to avoid over-filling, the collected water constitutes the water flow rate. Using the area of the pan lysimeter, the water flow rate, and the concentration, the average contaminant mass flow per unit area per unit time can be estimated, keeping in mind that it is a worst-case scenario.

Suction lysimeters collect soil water from unsaturated porous media in a small volume surrounding the porous ceramic cup at the terminus of the suction lysimeter. The contaminant concentration is a point sampling and the meaning is related to the geometry between the source and the suction lysimeter. A “nest” (several suction lysimeters at different depths) of suction lysimeters installed below a DRE trench will provide concentration variation with distance from the source. A line of suction lysimeters at a particular depth can provide an estimate of lateral spread from a line or point source. All data are concentrations only. More instrumentation is necessary to estimate mass flow rate using suction lysimeters.

A well installed into porous media is essentially a shallow water well. If the constituents of interest do not adhere readily to PVC, then the casing and the well screen can be made of PVC which is commercially available and easy to handle. Having a professional driller will give a log of the material that the well goes through and the driller can develop the well appropriately. These wells are typically 4” or 6” diameter and 25-100 feet deep. The cost of wells is approximately $40/ft. (2019 cost) . That cost goes up every year.

Installation in Broken Rock Spoil

Installation in broken rock mine spoil can be quite difficult. Digging an access trench parallel to the DRE trench to work in and then digging a horizontal slot into the side of the access trench to install the pan beneath the DRE trench is difficult because the broken rock A) interferes with digging a smooth, rectangular slot for the pan, and more importantly B) broken rock trenches are not stable and pose a serious collapse hazard.

As mentioned previously, one modification that is used in broken rock spoil is to excavate a hole in the spoil, and install a closed container (think bucket) filled with coarse -textured sand. An access tube to remove the sample from the lysimeter (bottom of the sand) is brought to the surface. The excavation is then backfilled with the excavated spoil. The lysimeters are sampled by pumping the leachate to the surface with an electric or hand pump. The concept is that the excavated material has just recently been drastically disturbed, so excavating and filling back will not cause significant changes to hydraulic properties and will reflect chemistry that is similar to the surrounding spoil (Lasley et al., 2010) .

Sampling broken rock mine spoil for groundwater contaminants can be accomplished by installing a drain line perpendicular to the gradient. The drain line has to intercept a saturated zone, at least at some point in time. The need for *a priori* knowledge may entail having some shallow observation wells to determine where the groundwater table is at different points in time before planning the drain line layout. The gravity drainage through can be sampled with an automated sampler or can be collected as a grab sample. The outflow of the drain line can be measured with a tipping bucket flow meter or a Doppler flow meter. The resulting data is time -stamped flow and concentration data from which mass flow rate of the contaminant can be calculated.

If the drain line is above the saturated zone, then conceptually, the contaminant originates on the soil directly above the drain line and the flow is directly downward, in response to a precipitation event. The source area for the contaminant is the length of the drain line multiplied by the width of the drain line. This allows an estimate of the average contaminant mass flow per unit area per unit time (e.g. kg N/hectare/year). This quantifies the impact of a practice.

Monitoring wells in broken rock spoil are very difficult to install. Conventional rotary drills usually won't go through this type of spoil. Rotary drills in broken rock mine spoil often break bits and parts become stuck in the bore hole. This wastes a lot of time and money and as a result, water quality wells installed in broken rock spoil are often drilled and developed using percussion or cable tool rigs. A cable tool rig (percussion drill) can usually be put in a well in this type of spoil but not easily, rapidly, or cheaply. Cable tool rigs raise and drop a drill string with a heavy carbide tipped drilling bit that chisels through the rock by finely pulverizing the subsurface materials. The impact of the drill bit fractures the rock and may increase the water flow into a well, compared to rotary drilling. During the drilling process, the drill string is periodically removed from the borehole and a bailer is lowered to collect the drill cuttings (rock fragments, soil, etc.) . Cable tool rigs are simpler and cheaper than similarly sized rotary rigs, although loud and very slow to operate.

If the boundaries of the spoil are well defined and there is a clear interface between the spoil and undisturbed porous media, wells can be drilled in the porous media very close to the spoil-porous media interface and screened at the depth of the spoil, then samples from these wells are fairly representative of the water in the spoil.

Monitoring for Regulatory Purposes

Monitoring for regulatory purposes often must be done with wells. In porous media, wells are relatively easy to install and monitor. A water table usually exists not too far from the surface. Using three wells in a triangle near the contaminant source can determine the gradient. A few more wells can then be installed and a monitoring network results. It is important to have a well up-gradient of the source, usually on or near the property line. This is a measure of concentration in the incoming water, sometimes called defensive monitoring.

The data from regulatory monitoring is sometimes dictated by the regulations. Concentration of some constituents may be the item in the regulations. In drinking water, 10 mg NO_3-N/L NO_3-N is the standard. Mass flow is not considered in most regulations.

Monitoring for Research

The overall purpose for scientific monitoring of DRE sites is to define the fate and transport of constituents in the entrenched biosolids. The data are used to define mass transport. The specific things that are measured and sampled are water flow rates as it varies with time and location in three-dimensional space, and constituent concentration as it varies with time and location in three-dimensional space. These two data sets are combined to provide mass transport data.

Typically, a large number of sampling locations and devices are necessary to clearly define mass transport. Installation and maintenance are not trivial components. There may be existing wells with existing data sets. These extra data sets can be used to describe some of the mass transport but are not normally sufficient.

The combination of a water flow rate and a constituent concentration (and some unit conversion) provide a mass transport rate data point. The total mass transported past a point in space is the integral over time of this mass transport rate data set. Analysis of all the mass transport at the various points in space will provide information about the movement of the constituent at the site. The same data may identify whether or not unsaturated flow is an essential component.

Data are usually a time series (or many time series) data sets) . Each data set will most probably have missing data points, and typically the data are not normally distributed. As a result, careful statistical analysis is required. By way of example, the ERCO DRE project resulted in 4,933 soil water samples collected from suction lysimeters and 746 samples collected from pan lysimeter. There were also eight monitoring wells located at the perimeter of the site and six wells were added at interior locations after the project funding ended. The monitoring wells had quarterly samples for a very long period of time.

Nitrogen Cycle Basics Relevant to DRE

In the 1970's, biosolids generators in the Washington, D.C. metro area utilized trenching as a disposal technique. Much of the early work for the original design of trenching and nitrogen dynamics was based on greenhouse and experimental sites. This large body of work conducted by USDA-Beltsville was used to develop the first deep row entrenchment project at ERCO that added the use of trees in the design. It required developing an N budget for DRE using hybrid poplar trees that took into account the distinct differences between surface application and previous DRE which did not include the use of trees.

The underlying concept of deep row entrenchment (DRE) is the development of a natural recycling system that utilizes a single application of biosolids to provide adequate nitrogen to fulfill the needs of hybrid poplar trees for a period of five to six years. Nitrogen is the primary nutrient that controls tree growth, but in biosolids it is predominantly in an organic form that is not available to trees or other crops unless it is transformed into nitrate, which is readily taken up by tree roots (Figure 12) . Organic nitrogen is fairly stable, but nitrate is easily leached into the water table, so the challenge is to balance the N provided without causing excessive leaching of nitrate into ground water where it can become a pollutant (in some cases, a danger to humans) and contribute to eutrophication. Nitrate is a regulated pollutant in drinking water with a maximum level 10 mg/liter. The DRE system used at the ERCO site had nitrogen losses from the deep rows well below the drinking water standard.

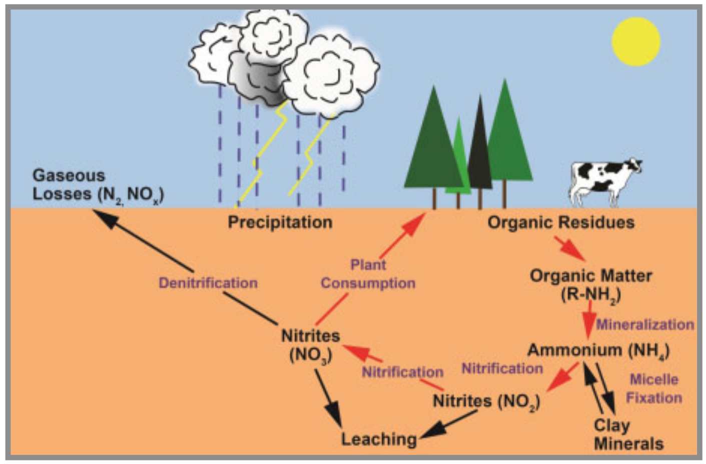

Figure 12. The nitrogen cycle, Pidwirny 2000.

To better understand how DRE works and differs from conventional surface application, it is essential to understand the basics of the nitrogen cycle (Figure 12).

When organic matter in biosolids or manure is exposed to oxygen, mineralization occurs. More specifically, bacteria in the soil convert the organic N to ammonium (NH_4) . On the surface, this can release a strong ammonia smell into the air which is offensive to most people. The strong odor creates many problems when biosolids are surface applied to farm fields. Up to 62% of ammonia is volatilized in surface application the first year but this is reduced to 16-22% when the biosolids are incorporated into the surface soil (Beauchamp et al., 1978) . Deep row entrenchment buries the biosolids so that no oxygen is available and essentially stops the mineralization process and ammonia volatilization. This explains why DRE eliminates the ammonia odor problem.

Biosolids also have another source of odor. There are many sulfur compounds in biosolids and these can oxidize to create obnoxious odors or simply volatilize and spread obnoxious odors. Entrenchment rectifies this odor problem.

The second step in the mineralization cycle is **nitrification** or the transformation of ammonium to nitrate. This process proceeds quickly when oxygen is available as is the case with surface application of biosolids. The nitrate is then available for use by field crops, trees, or other vegetation. However, in DRE nitrification is inhibited due to the lack of oxygen. The low temperatures and high soil moisture characteristic of DRE limits nitrification. The oxygen needed for nitrification in DRE is supplied by the *aerenchyma* structure in the tree roots which allow the formation of nitrate and the quick uptake by the roots to be used for tree growth. Without oxygen, the mineralization process stalls until oxygen becomes available.

Ammonium formed by the mineralization process can also be **immobilized** in the soil by clay particles that can hold the ammonium in the soil profile. In DRE, anaerobic conditions exist in the underground environment which essentially stops mineralization so the conversion to nitrate is stopped. However, ammonium that come in with the biosolids or is subsequently formed by organic nitrogen breakdown will attach to clay in the soil profile. Research has shown that soils composed of all sand do not only lack the clay particles needed to attract ammonium but are unable to maintain anaerobic conditions due to the coarse soil texture that allows oxygen to enter. The importance of some clay in the soil profile is critical to the DRE system.

Denitrification is the conversion of nitrate to nitrogen gas. The environmental conditions of the DRE system have anaerobic conditions, low temperature, and high moisture, which provide very favorable conditions for denitrification. Research has found that up to 60% of the N in biosolids may be lost to denitrification in DRE (Taylor et al., 1978).

The DRE system using hybrid poplar trees creates the following sub-surface conditions that minimize N mineralization until hybrid poplar tree roots reach the biosolids pack and provide oxygen to allow N mineralization and then nitrate (NO_3) uptake by the tree roots;

- Depressed biosolids mineralization rates in deep rows due to low soil temperature (~54°F), high moisture content, and low or no oxygen.
- Clay soil particles that bind with ammonia (NH_4) to immobilize nitrogen.
- High denitrification rates because of the combination of anaerobic conditions, ready supply of organic matter, appropriate anaerobic microbes, high soil moisture, low temperature, and presence of nitrate.
- Hybrid poplar roots that transport oxygen to the biosolids through the *aerenchyma*, take up large amounts of water, and utilize available nutrients.

Phosphorous Cycle and DRE

A great advantage of DRE is that trenching of biosolids deposits phosphorous in the soil profile where it will not contribute to P-laden surface runoff. Biosolids contain P and surface application of P-containing organic matter in Maryland is constrained due the P management regulations. Phosphorus is an essential element for plant and animal growth, but too much of it can accelerate eutrophication, the excessive richness of nutrients in a body of water which causes a dense growth of plant life and death of animal life from lack of oxygen. Nitrogen and P both affect eutrophication, but P is the critical element in most fresh water bodies. Eutrophication causes the undesirable growth of algae and aquatic weeds, as well as oxygen shortages resulting from algae and plant die-off and decomposition.

The Maryland Agricultural Nutrient Management Program (ANMP) began in 1989 but focused primarily on preparing farm plans that balanced the application of nitrogen with the needs of crops, thereby reducing nitrogen expenses and nutrient-rich runoff. In 1998 the Maryland Water Quality Improvement Act (WQIA) required nutrient management plans based on both nitrogen and phosphorous, along with other practices to reduce nutrient loss to the Chesapeake Bay.

Soil P exists in organic and inorganic forms. Unlike organic N, the breakdown of organic P is a relatively slow process, and once it occurs, the P rapidly attaches itself to organic matter and soil particles and becomes immobilized.

In most soils, the P content of surface soils is greater than that of the subsoil. When biosolids are added to surface soils, much of the P is fixed by the soil where it is applied, allowing for little movement down through

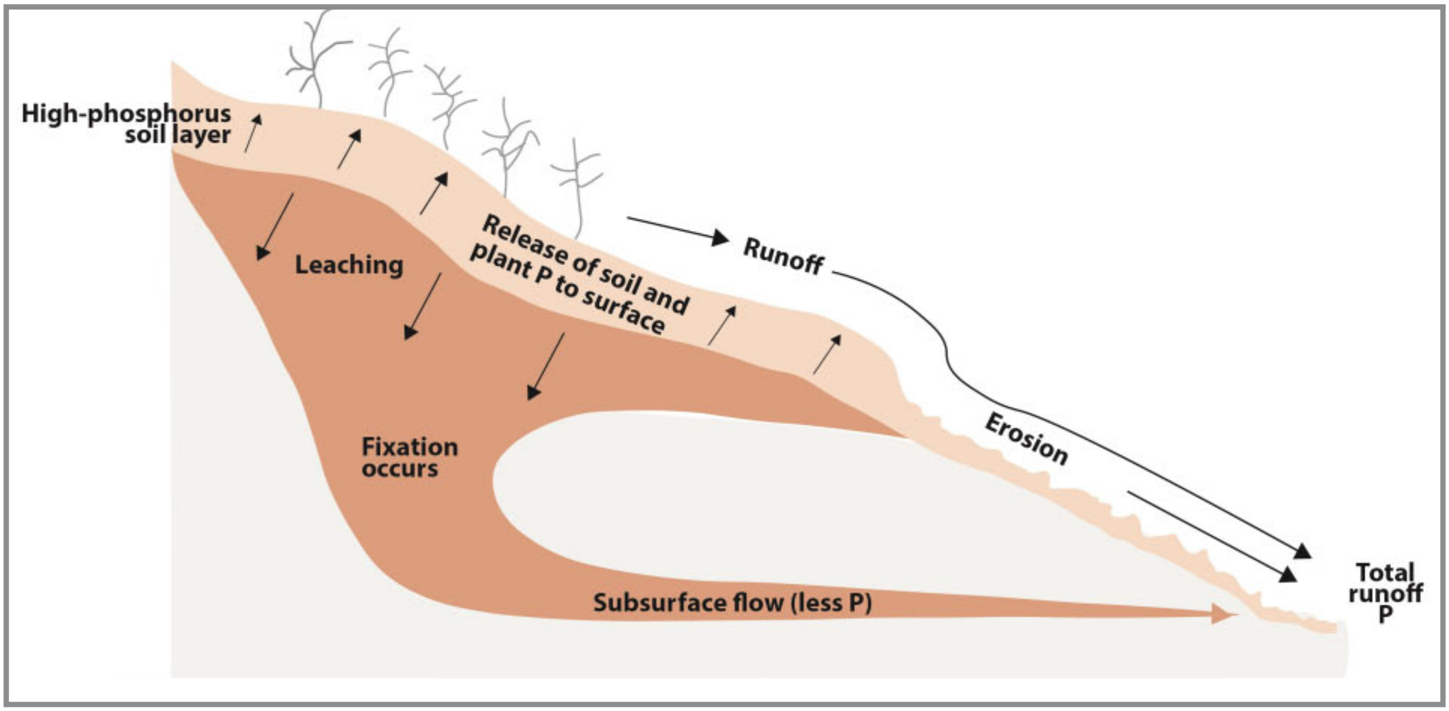

Figure 13. Diagram showing sources and movement of phosphorous from the landscape (Sharpley & Beegle 2001).

the soil. This results in P accumulating in higher levels in the soil surface.

Phosphorus gets in to water bodies primarily thorough surface runoff (Figure 13). This P may be dissolved P or P attached to sediment particles. Dissolved P is available immediately for uptake by algae but is a small percentage of the runoff. Sediment P has been fixed in the upper soil layers and during runoff provides a long-term source of P in water bodies. Up to 90% of the P transported from cropland is attached to sediment so erosion control is of critical importance to minimize P loss from surface application of biosolids, manure, or other sources.

The basic problem with applying biosolids and other manures is that P concentrations are higher than necessary for plant needs, relative to N concentrations. Because most crops require high inputs of N, relative to P to meet their growth needs, applications done based on N will provide excess P. The excess P will accumulate in the surface soil and be transported to nearby water bodies primarily attached to sediment particles. In contrast, DRE buries the nutrient source, which provides a solution to P runoff resulting from surface application of biosolids.

Foliar Leaf Monitoring

As hybrid poplar trees grow they mineralize nitrogen in the biosolids and uptake it to grow leaves and biomass. It is recommended to test the leaf samples for %N, %P, and %K. The percent foliar nitrogen and phosphorus in the leaves provides a measure of how rapidly biosolids are being utilized and is correlated with biomass growth. Maximum growth of hybrid poplar under fertilized conditions is thought to occur at 3.5% foliar nitrogen and 0.42% foliar phosphorous. However, fast growth is known to occur at 2.5-3.5% foliar nitrogen and 0.25-0.40% foliar phosphorous. If %P levels are low compared to %N then the trees may respond to the addition of phosphorous fertilizer.

Foliar leaf sampling is usually started in the second growing season. The time and collection of leaf samples is critical to get an accurate measure of % foliar N. The following protocol is recommended:

- Sample time during the peak of the growing season–early to mid-August in the Mid-Atlantic region.
- Sample the first fully expanded leaf which is usually five to seven leaves down from the terminal leader. If you sample leaves that are still actively expanding, the leaf will be pulling nutrients from the tree and give unrealistic value. If leaves are not expanding it will be a net exporter of nutrients and values may be low.

- Sample at mid-day when actively growing.
- Sample seven to 10 trees from each site and make a composite sample. To get a getter assessment across a site you can make a composite sample from three different areas across the site. The average of the three samples will provide a reliable average and possibly indicate any differences across the site.
- Put all leaves in a paper bag and allow to dry in a well-ventilated area. When dry send to a lab for analysis. Analyze for TKN and phosphorous.

Biosolids Monitoring

Annual sampling of biosolids in the deep row (known as the "pack") at each site is important to follow the trend in mineralization of the biosolids pack. The operational research in Maryland was required by permit to randomly sample a trench location in each planting. A backhoe was used to dig a trench perpendicular to the chosen trench location and then a composite sample was taken from different locations in the trend. The sample was analyzed and when 70% of the biosolids was mineralization the site could be harvested and reapplied as long as foliar %N samples were under 3.5% N.

More detail on where to take sample from the biosolids pack.

70% mineralization had occurred comes from Taylor et. Al. (1978). The Taylor paper was actually measuring the total N loss from the biosolids which could come from denitrification and mineralization. At this point the biosolids are stable. Could not lose any more N. Peat stage comes before 70% loss.

At 70% the pack is very thin and small. Only need to sample biosolids pack if you want to reapply. After seven years probably need to do it to get bond release on the application area.

Permitting Framework for DRE

Federal 503 Regulations

EPA developed a new regulation to protect public health and the environment from any reasonably anticipated adverse effects of certain pollutants that might be present in sewage sludge biosolids. This regulation, *The Standards for the Use or Disposal of Sewage Sludge* (Title 40 of the Code of Federal Regulations [CFR], Part 503), was published and became effective in 1993. These regulations are also known as "the Part 503 rule" and also as "Part 503."

It is important to note that disposal of biosolids is subject to state and local regulations as well as 503 regulations. State and other regulations may be more stringent than the Federal Part 503 rule.

The Part 503 rule includes five subparts:

1) general provisions,
2) requirements for land application,
3) requirements for surface disposal,
4) requirements for pathogen and vector attraction reduction, and
5) requirements for incineration.

The Part 503 standard includes general requirements, pollutant limits, management practices, operational standards, and requirements for the frequency of monitoring, recordkeeping, and reporting, Generally, the requirements of the Part 503 rule are self-implementing and must be followed even without the issuance of a permit.

The Maryland Department of Environment issues permits in Maryland. Authorization for states to administer the federal 503 regulations is through a process called "primacy." It is a federally-defined process that governs the review of the state to determine if the state can fulfill requirements of the 503 regulations. The process of authorization includes a public review, comment period, and a public hearing. Once granted primacy, the state administers federal 503 rules and state biosolids permitting regulations.

Land Application

The applier of biosolids must obtain information necessary to comply with the Part 503 land application requirements, apply biosolids to the land in accordance with the Part 503 land application requirements, and provide notice and necessary information to the owner or leaseholder of the land on which biosolids are applied. For DRE, the applier and the landowner are frequently the same entity.

Maryland regulations are found in Maryland's COMAR 26.04.06, which has approximately 75 parts. Because applications rates are greater than 50 dry tons per acre, the DRE process can only be permitted by either a "Research Project" (COMAR 26.04.o6.56-60) or an "Innovative Project" (COMAR 26.04.06.61-65). MDE is charged with insuring that a "system for routinely monitoring the quality of waters of the State at, surrounding, and beneath the site" is implemented.

A Sewage Utilization Permit for an Innovative Project should include:

- A description of the proposed project;
- A written authorization signed by the legal owners of the site [Note: For DRE, the applier and the landowner are frequently the same entity].
- A current site plan designating the property boundary lines, the exact acreage of the site, existing and proposed project structures, the location of any wells on the site and within 1/2 mile of the site, any residences or buildings on site and within 1/2 mile of the site, the proximity of the site to major roads in the area and any roads on the site, and surrounding land uses;
- Tax maps and liber and folio numbers for the parcels of land on which the project will be located and the names of the legal owners of the site;
- A current site-specific topographic map with a minimum scale of one inch = 200 feet and a contour interval of not more than five feet showing the areal extent of the site, and the location of any stream, spring, or seep within 1/2 mile of the site;
- A site-specific geologic and hydrogeological reports as required by the MDE, including a hydrologic map showing the location of the 100-year flood plain, if applicable, and the location of all soil tests, soil borings, and test pits on the site;
- A description of the source, type, and quantity of sewage sludge to be utilized;
- A detailed description of the utilization methods, processes, and monitoring procedures;
- Procedures for sampling, on-site record keeping, and reporting of the sewage sludge to be utilized.

Figure 14. The biosolids originally entrenched in the deep row (top left) are broken down by hybrid poplar roots as they penetrate the biosolids pack and utilize the nutrients for tree growth (upper right). Over time the biosolids are converted to a peat moss type consistency that does not smell and is very stable (bottom two photos).

This is the majority of the requirements for a permit application but is not all-inclusive. This is intended to demonstrate the level of detail an applicant should have developed prior to assembling a permit application.

The components of monitoring are subject to MDE approval and can be extensive and expensive. Once the monitoring system is approved and in place, MDE can change the requirements "to include a new condition as may be required by a new law or regulation, to clarify permit conditions, or for other good cause" (COMAR 26.04.65). In summary, the permit process is very complex and should not be taken lightly. To obtain approval, the applicant can count on spending a significant amount of time and money.

Regulatory Oversight of DRE at ERCO Site

ERCO operated the commercial DRE enterprise from 1983-2013 on 93 acres located within a larger property. MDE, the regulatory authority, required stringent regulatory monitoring of wells to detect leaching of metals, nitrogen, or other nutrients into the water table. Seven monitoring wells ranging from 20–100 feet were installed since 1983 and checked biannually for nutrients, pH, metals and coliform. After 31 years, no elevated level of any parameter was detected such as nitrate or heavy metals.

The fate of nitrogen in the biosolids and how the trees utilize it was the basis of the permit application. The section on the nitrogen cycle provides more details but for the operational permit, two parameters had to be met before the nitrogen in the biosolids were considered utilized and stable enough to justify tree harvest, retrenching, and reapplication.

1. **70% of the nitrogen in the biosolids was mineralized**–ERCO was required to take an annual sample from the biosolids pack in the trench in each 10-acre section to determine how much of the nitrogen has been mineralized. A backhoe was used to cut across the trench (Figure 14) in a random location and biosolids samples were taken and analyzed. Over the years the amount of nitrogen in the biosolids will continue to decrease as organic N in the biosolids is mineralized and converted to nitrate and taken up by tree roots or undergo conversion and lost through denitrification, storage, etc. Approximately 10 acres were treated each year at the ERCO site starting in 1984. Over the course of the 31 years, most of the sections were harvested and retrenched two to three times.

Figure 15. Foliar leaf samples are taken in August to assess N levels.

2. **Foliar Nitrogen Levels Below 3.5%**–As the organic N is mineralized in the trenches, nitrate is taken up by the tree roots. The percent of foliar N in mature tree leaves (Figure 15) provide an easy-to-measure indicator of the fertilization level of N of the trees. Since the biosolids are the only source of N in the system, higher levels of % foliar N indicate higher amounts of N uptake. This can be seen visually in the size, development, and sap extrusion, but foliar N provides a quantitative measure. Based on available research of hybrid poplar fertilized with biosolids, when foliar N levels go below 3.5% the trees are losing the fertilization effect of the biosolids, and the site can be harvested, retrenched, and reapplied.

Issues with Regulatory Framework from a Business Point of View

The existing innovative practice process is open-ended and has no assurance of success. Specifically, regulations state that requirements be included or changed "to include a new condition as may be required by a new law or regulation, to clarify permit conditions, or for other good cause." Hence, any number of monitoring wells and/or surface water monitoring stations may be required. Samples may be required to be tested for any number of constituents (It is not likely that MDE would require testing for something that was not in the original biosolids analysis). Additionally, new wells and monitoring stations can be required after the initial permit is granted.

To a business, this indicates that the initial expenses to establish monitoring and sampling stations may not ever

Figure 16. Location of ERCO Tree Farm in Prince Georges County, MD.

satisfy the criteria for a new permit and the expenses may be a total loss. Furthermore, significant additional expenses could arise at a later point in time, to the extent that the DRE system would not be economically sound. Essentially, establishing DRE could be prohibitively expensive with no guarantee of eventual success and subsequent additional expenses could throw the economics out of balance, forcing closure of the enterprise.

If a set of sampling and monitoring requirements for DRE work, either set in COMAR or published by MDE as a statement of policy, could be firm and stable over time, a business could examine the economics on paper and might be more willing to move forward.

University of Maryland Research at ERCO

ERCO was recognized in 1990 for two separate awards for Tree Farm Sewage Sludge Utilization, from the National Association of County Health Officials and the National Association of Counties. Even though the monitoring showed no signed of nitrate leaching from the site, regulators sought more detailed information. Starting in 1992 ERCO partnered with the University of Maryland to initiate some research projects to grow some other species in addition to hybrid poplar. In 2000, UM faculty partnered with Washington Suburban Sanitary Commission (WSSC), Metropolitan Washington Council of Governments (MWCOG), MDE, and ERCO, Inc. to develop a research proposal that would implement intense water quality research and determine nitrogen changes in DRE using different application rates. Almost $1 million was invested in the research. The research site was located in Prince Georges County, Md. (Figure 16).

ERCO Research Instrumentation

The research project focused on gravel mine reclamation using biosolids in deep rows as a nutrient source and hybrid poplar trees as the stabilizing crop. The project took place from January 2002-April 2009 on a three-acre plot within the operational ERCO site that had previously been applied with biosolids at the rate of 172 dry tons per acre. The study included biosolids application rates of 172, 345, and 517 dry tons per acre which amounts to 17,400, 34,800, and 52,000 lbs. N/acre, respectively. Three tree densities of 0, 300, and 450 trees per acre were studied. To better understand the movement of water and nutrients from trenches, soil water samples were taken from suction and pan lysimeters (Figure 17) located under and around the biosolids trenches and analyzed for total nitrogen, ammonium, nitrite, and nitrate.

Over the course of seven years, nitrite and nitrate concentrations were mostly non-detectable or less than 10 mg/l, which is the threshold for drinking water quality concerns.

Well or standpipes were inserted into the biosolids pack to better understand how the trenches dewatered and changes in nitrogen that occurred. Moisture in the biosolids leaves from the top down over the course of several years. It was difficult to quantify the mechanism for dewatering (drainage versus plant uptake). For the first two years, the standpipe water levels responded to precipitation events, but after the second year, water levels were at the bottom of the trench and did not change. This suggests that the water was drawn out by the growing tree cover and left the surrounding biosolids and nearby soil unsaturated. When precipitation events occurred, water infiltrated, but there was sufficient soil storage to take up the water without resulting in free standing water in the trench.

For the first three years of the study, zero nitrate left the DRE system. Ammonium was immediately released into the soil surrounding the biosolids pack. The ammonium concentrations decreased dramatically with distance from the biosolids, falling from 2100 mg N/L at 6 in. from the biosolids to 400 mg N/L at 24 in. from the biosolids. In the end, nitrate concentrations under the deep rows are lower than those found beneath a well-managed cornfield despite having at least 100 times more nitrogen in the DRE system.

The two lower biosolids application rates of 172 and 340 dry tons per acre kept the depth of the biosolids pack

Figure 17. (top left) Suction lysimeters are a PVC tube with a porous ceramic tip that is kept under suction to sample soil water. The plastic line allows the collected water sample to be extracted from the surface and suction then reapplied to collect another sample. (top right) A mud made of native soil is put on the ceramic cup during installation to insure good contact and moisture movement. (bottom left) Pan lysimeters constructed of stainless steel capture vertical flow. Surface screening on the pan stops soil from entering the pan. (bottom right) The bottom of the lysimeter is in a shape that allows good contact with soil above it during installation and will retain approximately 7 liters. The lower part of the collection pan is connected via a plastic line to the surface and allows the extraction of the sample water on a regular basis.

within reach of the tree roots and allowed safe operation of machinery. However, the highest rate of 517 dry tons per acre were operationally difficult to install within four feet of the surface and demonstrated higher rates of nitrogen leaching and loading that suggests very high application rates should not be used for DRE, both from a pollution standpoint and from an installation safety standpoint.

ERCO–Water Quality

Biosolids were applied using the deep row technique at rates of 171, 342, and 513 dry tons per acre, which is one time, two times, and three times the current permitted application rate at the ERCO site.

Suction Lysimeter Results

Suction lysimeters sample water, typically in an unsaturated zone. This pore water is in the pore spaces between the soil solids and may not move much for quite a long time. Therefore, it is exposed to the nutrients in the soil matrix and has the opportunity time to dissolve nutrients. Samples represent water in the soil matrix, but samples are not representative of water that migrates to the saturated zone. In the saturated zone, nutrient concentration is invariably lower than pore water in the soil matrix.

Soil water samples were collected and analyzed between 2003 and 2009. Approximately 4,933 discrete water samples were obtained from the various suction lysimeters installed in the research plots. Of these, fewer than 5% (222 samples) exhibited nitrate concentrations in excess of 10 mg/l. Over the study period, the average concentration in the suction lysimeters was 3.981 mg NO3-N/L. For the first two years (2003-2005), the nitrate concentration was uniformly non-existent. Our hypothesis is that the biosolids were encased in a cool wet and, most importantly, anaerobic environment which prevented organic nitrogen from converting to ammonium and subsequently to nitrate. During the subsequent years, nitrate concentrations from the suction lysimeters were less than for continuous corn crops fertilized with commercial fertilizers and less than for corn fertilized with surface-applied biosolids. Therefore, this method does not result in the release of nitrate from the deposited biosolids until the biosolids are reached by the tree roots, and then this method releases less nitrate to the soil water than well-managed conventional agriculture releases to saturated subsurface water during the following approximately four years through the harvest of the trees.

Table 1 shows the nitrogen loading in units of mass of nitrogen/unit area. For people familiar with typical corn crop application rates, the numbers are relatively huge. A six-year loading at 160 lbs. N/acre (typical for corn on low to average fertility soil) would be 960 lbs. N/acre. The reasons for the much larger loading are a) denitrification can take as much as 40% of the nitrogen (Taylor et al., 1978), b) at least 1% of the nitrogen remains as relatively intractable N in the organic matter, c) some of the nitrogen is immobilized in the soil as ammonia bound to the clay, d) the crop requirements are very different for an annual crop (corn) that requires nutrients for 90 days or less compared to a perennial crop (trees) that requires nutrients for at least 270 days per year, and e) the trees annually increase in biomass, and hence, nutrient requirements every year.

Table 1. Treatment rates, depth of biosolids in the trench, total trench depth, and approximate biosolids application rate.

Application Rate (lbs. N/A)	Inches of Biosolids	Total Depth of Deep Row in Inches (12" overburden)	Dry Tons / Acre
4,000	12.5	24	172
8,000	25.0	37	345
12,000	37.5	49	517

Nitrate Variation with Application Rate

The soil water samples from the suction lysimeters were analyzed and segregated by biosolids application rate. Results were plotted for the period 2003-2009 and are presented in Figure 18. Each data point for the three biosolids application rates represents an average of approximately 45 samples. The control values represent the average of approximately 15 samples.

For the first two years (2003-2005) after biosolids application, the nitrate concentration was uniformly non-existent. Over time, as the hybrid poplar roots begin to contact and penetrate the biosolids, the *aerenchyma* (Stettler et al., 1996) in the roots transport oxygen and introduce it to the biosolids, allowing for organic nitrogen conversion to nitrate. Because the roots are right where the nitrate was forming, much of the nitrate is taken up as it formed. Increases in soil water nitrate concentrations were first exhibited in the 2005 samples from lysimeters near deep rows containing the lowest application rate (one times the permitted rate). Concentrations of soil water nitrate increased in the two times permitted rate in samples obtained in 2006, and the highest application rate began generating nitrate in 2007. These data support our hypothesis that the biosolids remain anaerobic until reached by the poplar roots. The deep-row environment at the ERCO site retards the mineralization of organic nitrogen to ammonium and subsequent conversion to nitrate. The presence of the roots (and their contribution to the mineralization process) mitigates impacts from excessive nitrate formation as the roots will generally take up the nitrates as they are formed.

We believe that, because the row containing the three times application rate was three times as deep as the row for the one time rate, roots did not fully come into contact with the biosolids for a longer period. Moreover, the greater mass of biosolids within the deeper row in the highest applications rate likely maintained the anaerobic environment for a longer period when compared to the lower application rates.

The data exhibit seasonal fluctuations; during the active poplar growing season, soil water nitrate concentrations are reduced to about "background" levels. Soil water nitrate concentration peaks generally occurred in the October-December sampling periods which represent that time after the end of the active growing season (tree removal of nitrates) when conditions may still be slightly favorable for continued nitrate formation (oxygen may

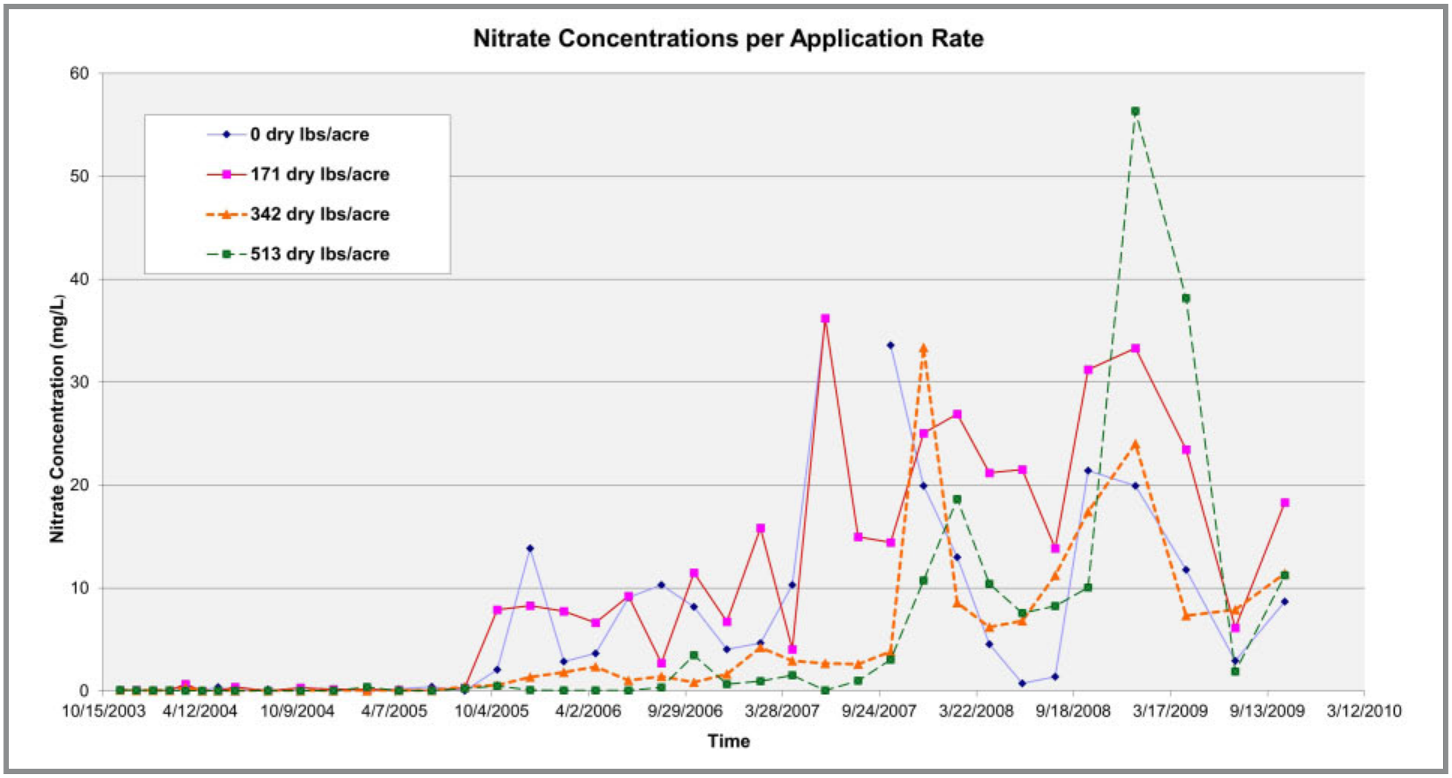

Figure 18. Average nitrate concentrations in suction lysimeters beneath and adjacent to biosolids entrenched in deep rows for each application rate.

be present and subsurface temperatures are about at their peak).

Based on our experiences and the data from these soil water analyses, we do not recommend the highest rate. Developing the larger deep row, covering it. and then working on the surface proved difficult. Moreover, the data does infer that the higher rate could produce higher seasonal soil nitrate concentrations relative to the other two rates.

Nitrate Variation with Depth

Soil water nitrate concentrations in all soil water samples varied with depth. However, because graphs all included time, the variations are hard to clearly identify visually. There were lateral lysimeters installed 15 and 30 cm to the side of the biosolids at the level of the bottom of the trenches. These lysimeters averaged 5.4 mg NO_3-N/L The lysimeters immediately below the biosolids (15 cm depth) averaged 4.5 mg NO_3-N/L. These collectively constitute the “near” samples. The lysimeters at 30 cm and 60 cm below the biosolids averaged 1.3 mg NO_3-N/L. These lysimeters constitute the “deeper” samples and it is clear that there is a higher nitrate concentration in the soil closer to the biosolids. The data suggests that the nitrate losses from the deep rows are generally not moving far from the deep row–there may be some increases in soil water nitrate concentrations in the soils bounding the deep rows, but there does not appear to be substantial increases in soil water nitrate concentrations at depth below the deep rows.

There was no continuous loss of nitrate from the deep rows over time and, in fact, most of the analytical data indicated that nitrate movement from the biosolids was generally infrequent and concentrations in the soil water were quite low.

Ammonium in Suction Lysimeters

Ammonium (mg NH4-N/L) concentrations found in the suction lysimeters are plotted in Figure 19. Consistently, the control (no biosolids application) had ammonium concentrations in the suction lysimeters just above zero. For the treatments, between October 2003 and December 2004, the ammonium level rose from approximately 400 mg/L to approximately 625 mg/L. This rise was independent of the application rate. Then in 2005 and from there on, the lowest application rate was fairly consistently at a lower concentration level than the other two rates.

There was a jump in December 2004 in the concentration from the middle application rate (39,300 kg N/ha). The concentration rose from approximately 590 mg/L to approximately 775 mg/L. The middle application rate

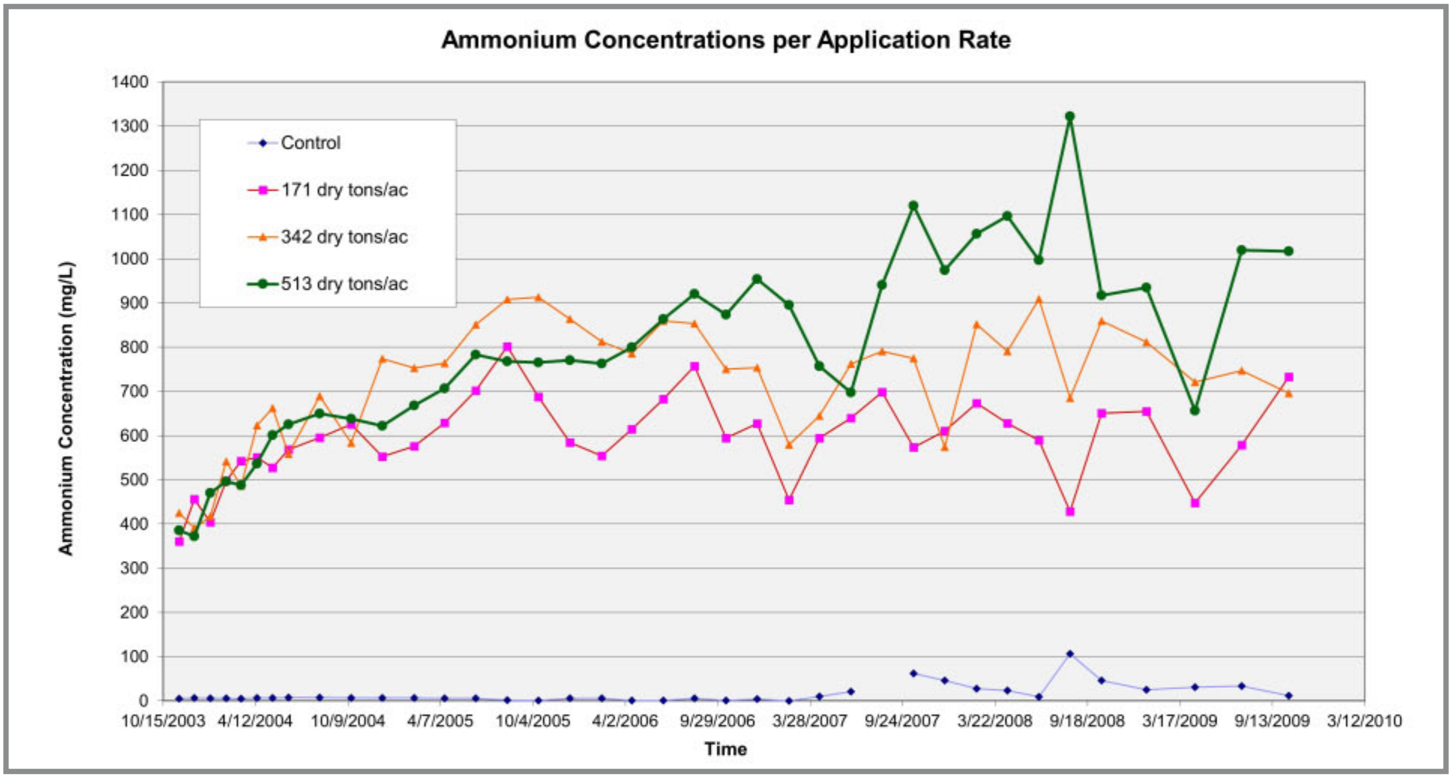

Figure 19. Monthly average ammonium concentration in suction lysimeters. (Nov. 2003-Oct. 2009).

concentration remained elevated above the lowest rate and the highest rate until March 2006. Between August 2005 and August 2006, both the low application rate (19,650 kn N/ha) and the middle application rate (39,300 kg N/ha) dropped to a low in February-April 2006 and then rose to a temporary high in August 2006. This is most likely a seasonal variation. However, the levels dropped by about 100 mg/L over that year. From March-October 2006, the concentration mirrored the application rate.

Additionally, the increase in concentration has either leveled off or has started to decrease since sometime in mid to late 2005. This was the case for all application rates.

Effects of time may be different for each application rate because the heavier rate is deeper than the lower rate. The lowest rate peaked in August 2005. The middle rate peaked in October 2005, and the highest rate peaked in August 2006. This may be due to the time required for tree roots to grow deeper for the heavier application rates. When the tree roots appear, oxygen is introduced and microbial action may change dramatically.

Ammonium with Depth

Figure 20 represents the effect of depth or the distance ammonium is migrating. Each data point represents 27 observations (three replicates times three application rates times three tree densities). The controls (no biosolids) were not plotted.

First, ammonium is clearly increasing over time. At 15 cm below the trench, the ammonium level has increased from approximately 1000 mg N/L in November 2003 to approximately 2000 mg N/L in November 2005. At the 60 cm depth, the increase was from approximately 175 to 400 mg N/L. The 30 cm depth was uniformly in between. The ammonium levels at the 30 and 60 cm depth may have leveled off. The ammonium levels at the 15 cm depth may be decreasing. Additional data are necessary to draw any meaningful conclusions.

Pan Lysimeter Results

Nitrate Variation with Application Rate

The data in Figure 21 represents nitrate concentrations in the pan lysimeters between November 2003 and October 2006. Note that the Y-axis is a log scale. Differences between points that are below 0.1 mg/L are probably not meaningful. The control data points are the average of three data points and the levels are the average of nine data points. The wide variation in data values in the first six months is probably not reflective the actual water quality. Disturbances to the soil and the installation of the pan lysimeters can result in invalid measurements

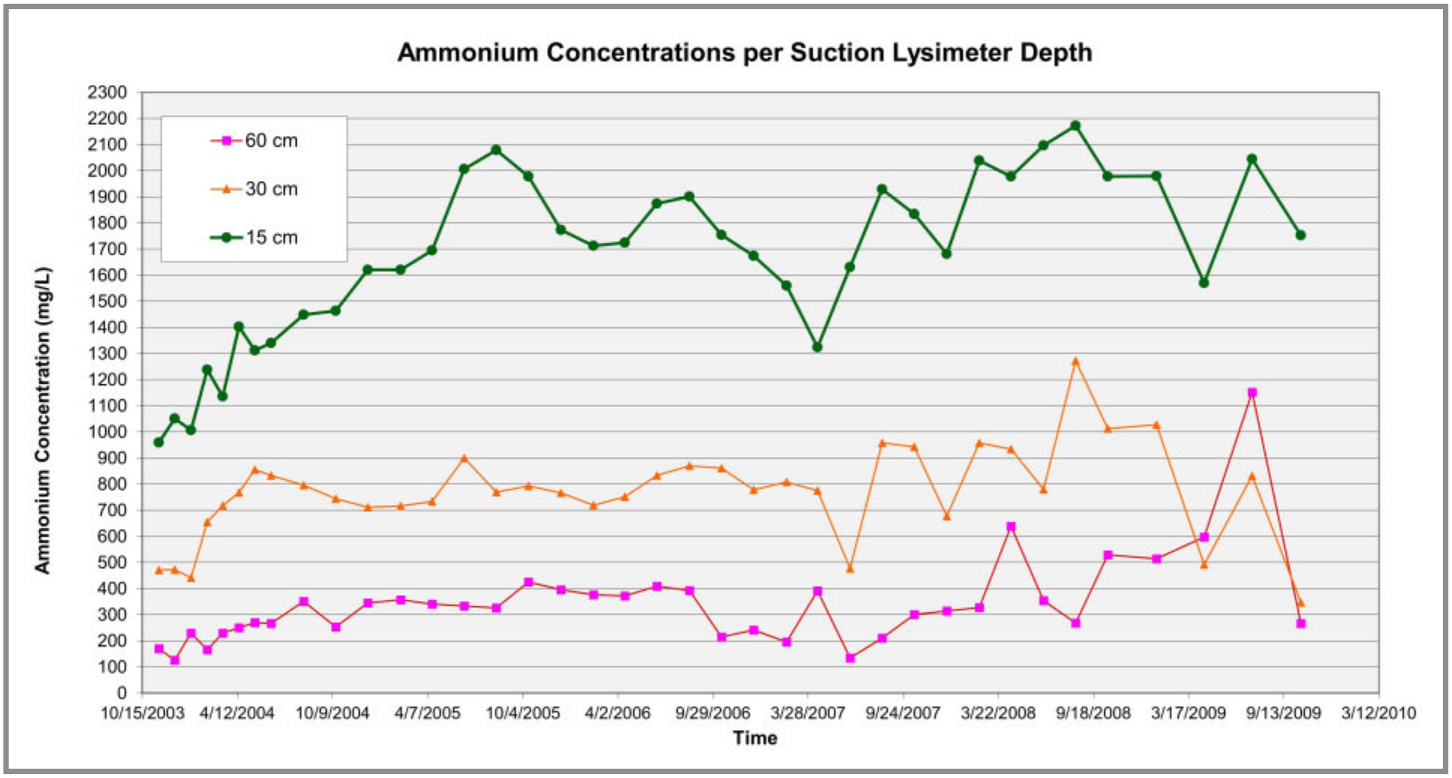

Figure 20. Monthly average ammonium concentration in suction lysimeters, sorted by depth below (vertical) and to the side of (lateral) the biosolids trench. (Nov. 2003-Oct. 2009).

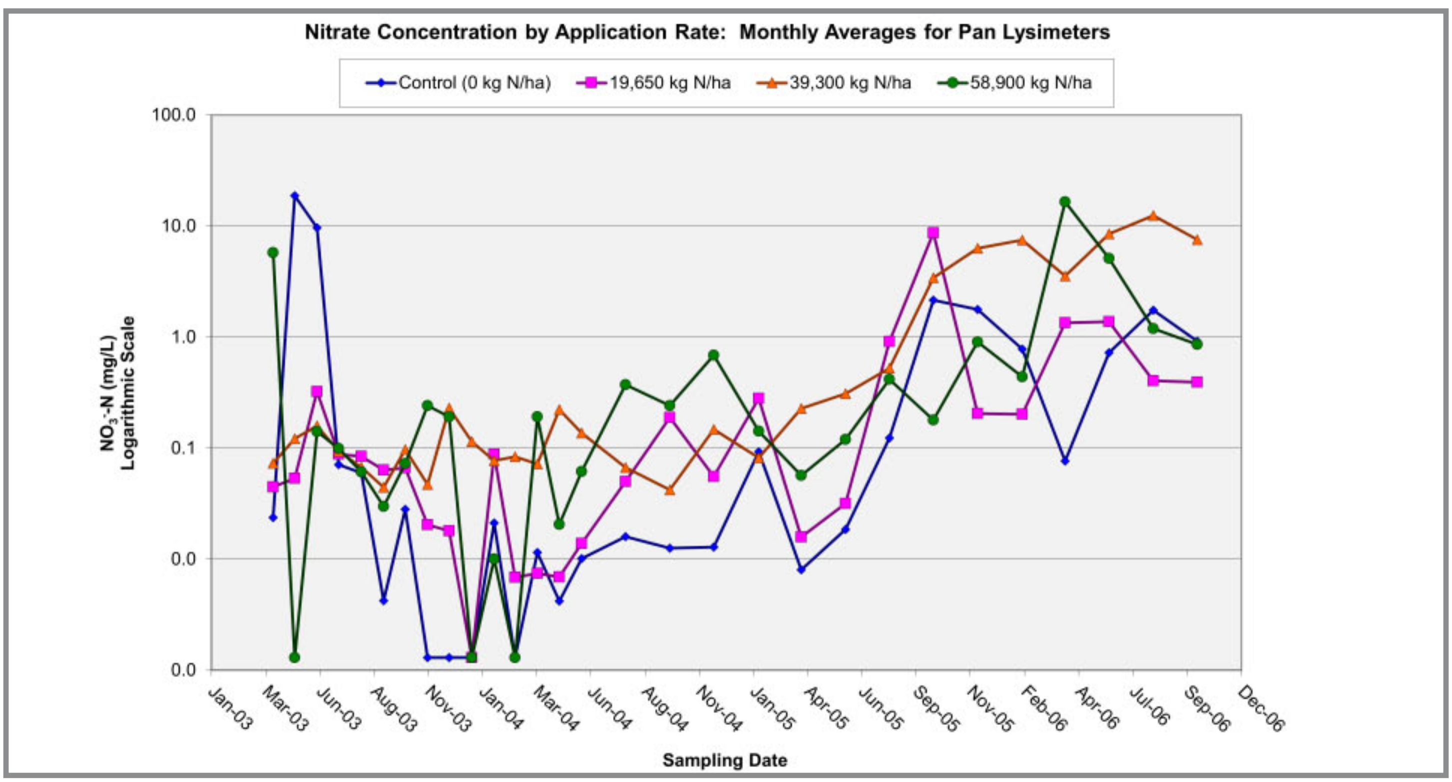

Figure 21. Monthly average nitrate concentration in pan lysimeters. (Nov. 2003-Oct. 2006).

at the initiation of the experiment. In approximately July 2005, nitrate began to appear in the water sampled by the pan lysimeters. The levels typically have been below 10 mg/L. At this point, variation in the biosolids application rate is not clearly related to the nitrate concentration. The control (no biosolids) also went up during the same period of time. This suggests that there may be a meteorological change that is affecting the nitrate loss from the surface. However, the control reached levels of 2-3 mg/L while the treatments reached levels of 10 mg/L. Additionally, the trend was upward from approximately January 2005 through October 2006.

The highest value was observed in the control (13.9 mg/L) for the November 2005 sampling. The highest two application rates (58,900 kg N/ha and 39,300 kg N/ha) had the lowest nitrate concentration and the lower two application rates had the highest nitrate concentrations, hovering around 10 mg/L. Between July 2005 and October 2006, all nitrate levels seemed consistent at between 1.0 and 10.0 mg N/L except for the highest application rate, which seems to be starting an increase toward 10 mg N/L from June-October 2006. The explanation for the lowest application rate increasing first may be that as application rate increases, depth increases. Hence temperature, oxygen, and microbial activity are all delayed in the heavier rates and, as a result, the formation of nitrate may be delayed in the deeper trenches.

Nitrate concentration draining from corn on agronomic soils using fertilizer or biosolids as the N source is significantly (as much as triple) higher than nitrate found beneath the deep row forestry system, even for the highest biosolids application level.

Ammonium in Pan Lysimeters

Ammonium (mg NH_4-N/L) concentrations found in the pan lysimeters are plotted in Figure 22. Clearly, the control was well below the treatments. This was not true for the nitrate values. At about February of 2004, the three application rates had ammonium concentrations of 450-600 mg NH4-N/L. By September 2006, these values had dropped to 175- 320 mg NH4-N/L. This is clearly a downward trend. The heavy rate of application exhibited a peak from January 2005 through August 2005 that was not exhibited by the other two application rates. This suggests that something in the system is not responding the same in the heaviest rate. A preliminary assessment is that the heaviest rate may not be appropriate.

Orthophosphate

Orthophosphate was monitored heavily during the first 18 months. Of approximately 220 suction lysimeter

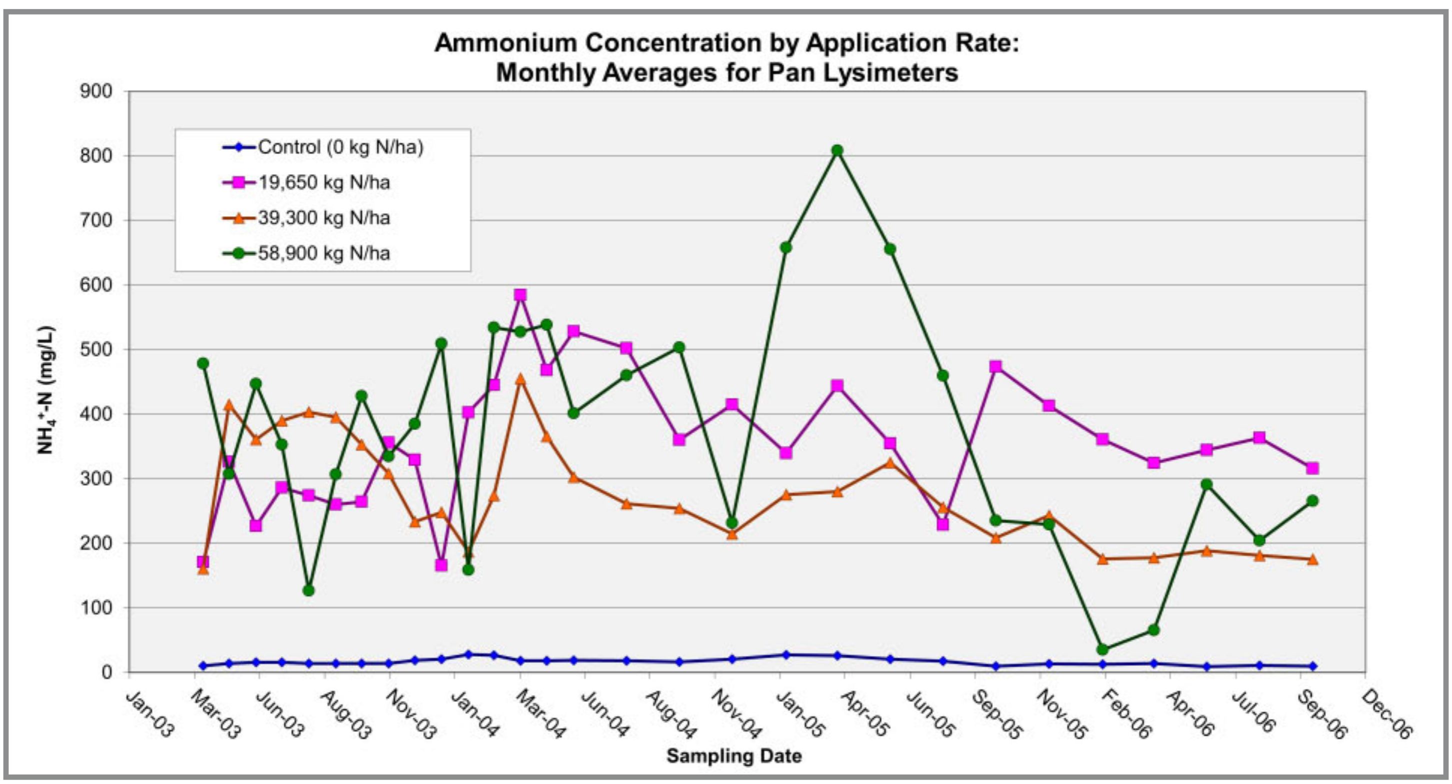

Figure 22. Monthly average ammonium concentration in pan lysimeters. (Nov. 2003-Oct. 2006).

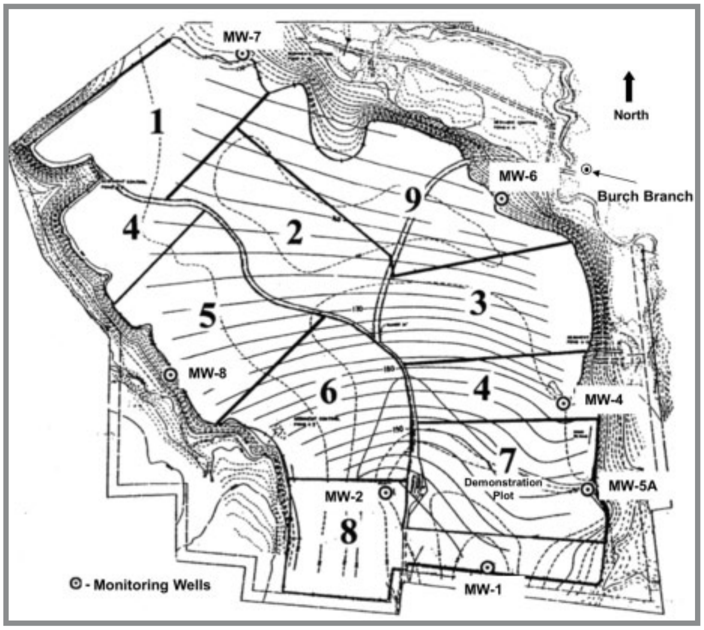

Figure 23. Plot layout of ERCO site showing nine 10-acre sections planted with hybrid poplar, and seven monitoring wells. Study site was located in 3-acre area in section seven. Topographic lines show estimated ground water potential lines.

samples, samples, eight samples were above 1.0 mg P/L. There was no trend. It was expected that phosphorus would bind to soil particles.

Well Results

There are seven functioning groundwater monitoring wells installed at the Tree Farm site (Figure 23). The first well, installed in November 1982, is designated MW #2, and is situated within 100 feet of the ERCO trailer. The well is cased to 31 feet and screened from 31-41 feet.

Additional monitoring wells have been installed in conjunction with permit amendments/modifications, especially those related to the inclusion of additional acreage. Well descriptions are as follows (Table 2).

Table 2. Monitoring well installation data.

Well Number	Date Installed	Screened Depth
1	7/26/88	70’-80’
2	11/15/82	31’-41’
4	7/14/88	25’-35’
5A	3/28/89	28’-38’
6	10/8/90	107’-127’
7	10/8/90	77’-97’
8	10/8/90	80’-95’

Figure 23 provides estimated ground water contours using data from all the wells located at the ERCO Tree Farm. The solid lines represent ground water potential contours and the dashed lines represent topographic contours. In Figure 23, the groundwater potential decreases from Section 8 toward Section 9. Overall, these contours show a general hydraulic gradient toward Burch Branch, which flows past the Tree Farm site to the north and east. An unnamed tributary to Burch Branch flows along the western boundary of the ERCO Tree Farm. Based on the ground water contours and the presence of perennial streams on three sides of the Tree Farm, water quality related to biosolids management operations can be reasonably well estimated by reviewing the historical analytical data from both the wells and the surface waters draining the site.

A water sample, intended to be representative of ground water conditions prior to biosolids application, was obtained by the Prince George's County Department of Health (then Department of Health and Mental Hygiene) for the Maryland Department of Environment on November 9, 1982. Analysis of this sample yielded the following results (Table 3):

Table 3. Results from a single sample, collected 11-9-82 as a pre-application sample.

pH	7.8 units	**lead**	0.01 mg/l
nitrate	1.5 mg/l	**iron**	1.3 mg/l
color	60 units	**zinc**	0.05 mg/l
cadmium	0.005 mg/l	**hardness**	65 mg/l
copper	<0.01 mg/l	**fluoride**	2.45 mg/l
sodium	80 mg/l	**total residue**	364 mg/l
alkalinity (total)	98 mg/l	**mercury**	<0.0005 mg/l
chloride	30 mg/l	**manganese**	<0.01 mg/l
turbidity	24 units		

Groundwater monitoring data from 1983 through 1994 indicate little evident change in overall groundwater quality due to biosolids application. A detailed review of the chloride, nitrate nitrogen, cadmium, lead, and fecal coliform results was performed. Chlorides are anionic compounds that are not well retained in soils and are commonly found in biosolids. They are easily leached from the soil and are often utilized as an indicator of pollution potential in groundwater. Nitrate nitrogen (Figure 24) is an anionic compound that may be introduced from high levels of fertilizer application and, at excessive levels in water supplies, has been demonstrated to cause health problems in cattle and

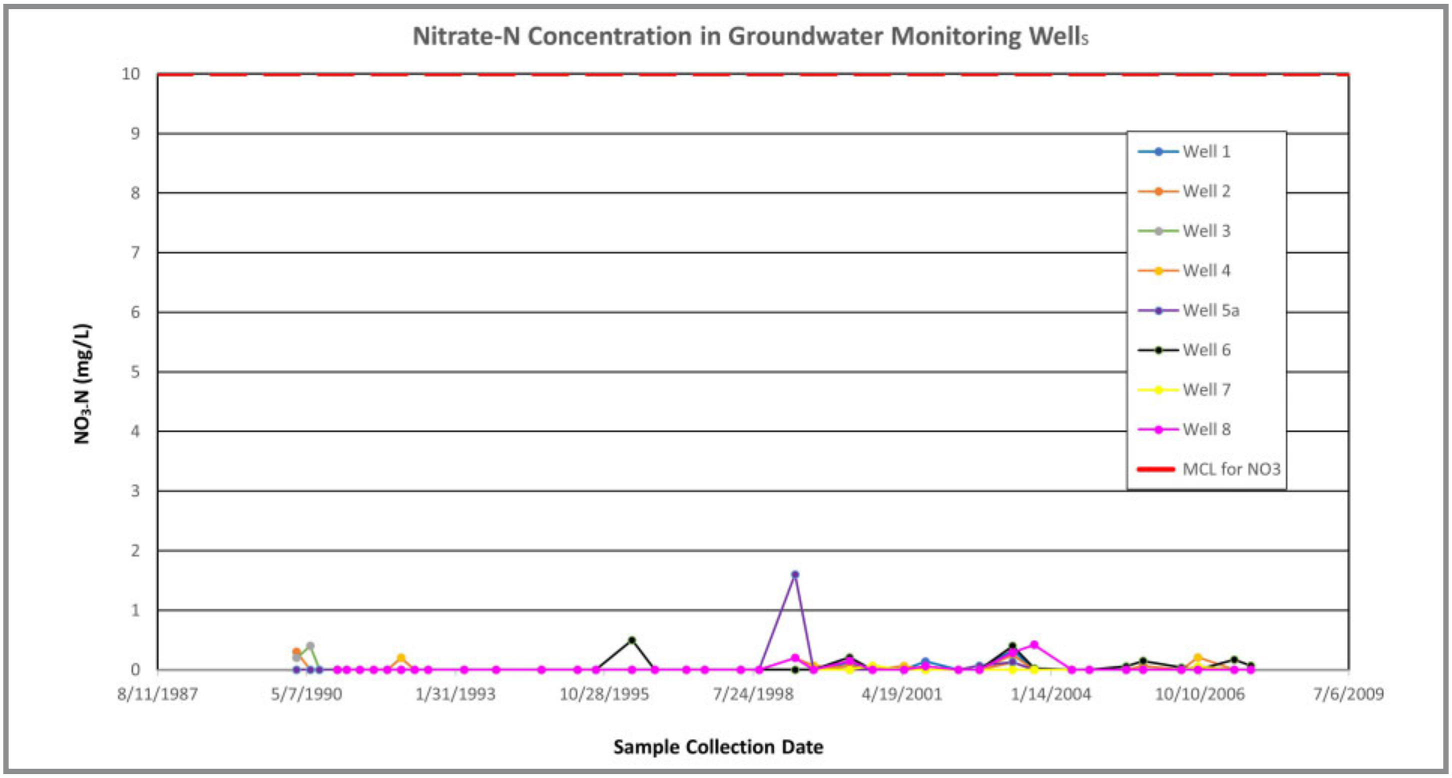

Figure 24. Nitrate values (mg/L NO_3-N) for each of the eight monitoring wells.

infant humans. The presence of nitrates in ground waters is often an indication of fertilizer nitrogen application in excess of plant needs.

Figure 24 shows that there was no well contamination from the eight monitoring wells over the 13-year period 1990-2003.

Figures 25 and 26 represent the ammonia data for the ERCO site monitoring wells. As with many of the water quality parameters evaluated for the ERCO site, there is no drinking water standard for ammonia. Therefore, referring to a "critical" level has no meaning. However, ammonia is a nutrient of concern to the Chesapeake Bay. Therefore, most wastewater treatment plants in the region have ammonia limits in their discharge permits. The Blue Plains effluent limit for ammonia is 6.5 mg/L. Figure 25 places the historical ammonia concentration in the monitoring wells at the ERCO site into context by using the Blue Plains limit as a benchmark.

Figure 26 places the ammonia concentration in all wells over the period in context with background levels, as can be quite well seen on Figure 26, in May 2002. Well 2 had an ammonia concentration spike of 85 mg/L. The subsequent reading was 1.4 mg/L. This is unusual and one-time events suggest that the well may have direct surface linkage, the sample may have been contaminated, or the integrity of Well 2 may be questionable.

Ammonia in groundwater also usually indicates an elevation in nitrates as ammonia tends to be quickly converted to nitrate in this environment. So this spike in Well #2 is also curious insofar as the water sampled on this date did not exhibit elevated nitrate levels (reported as a non detect). In any case, it is clear that the levels of ammonia in the deeper wells are un-remarkable, always remaining between non detect and less than 1.0 mg/L.

For all wells, nitrate water concentrations were most commonly at or less than detection limits. In the most recent sampling and analysis event, the nitrate concentration in all wells at the Tree Farm was determined to be below detection limits. Occasionally, nitrate concentrations were reported at higher levels than detection limits but never did the level reported approach the drinking water standard of 10 mg/L.

Subsequent Well Study

In December 2014, a post-closure well study was completed by Geo-Technology Associates, Inc. (GTA) from Abingdon, MD for the site. Biosolids application ceased in May 2008. Additional wells were installed in 2012 and the first data were collected in August 2012. The final report was presented in December 2014. Eleven monitoring wells were sampled for the GTA report:

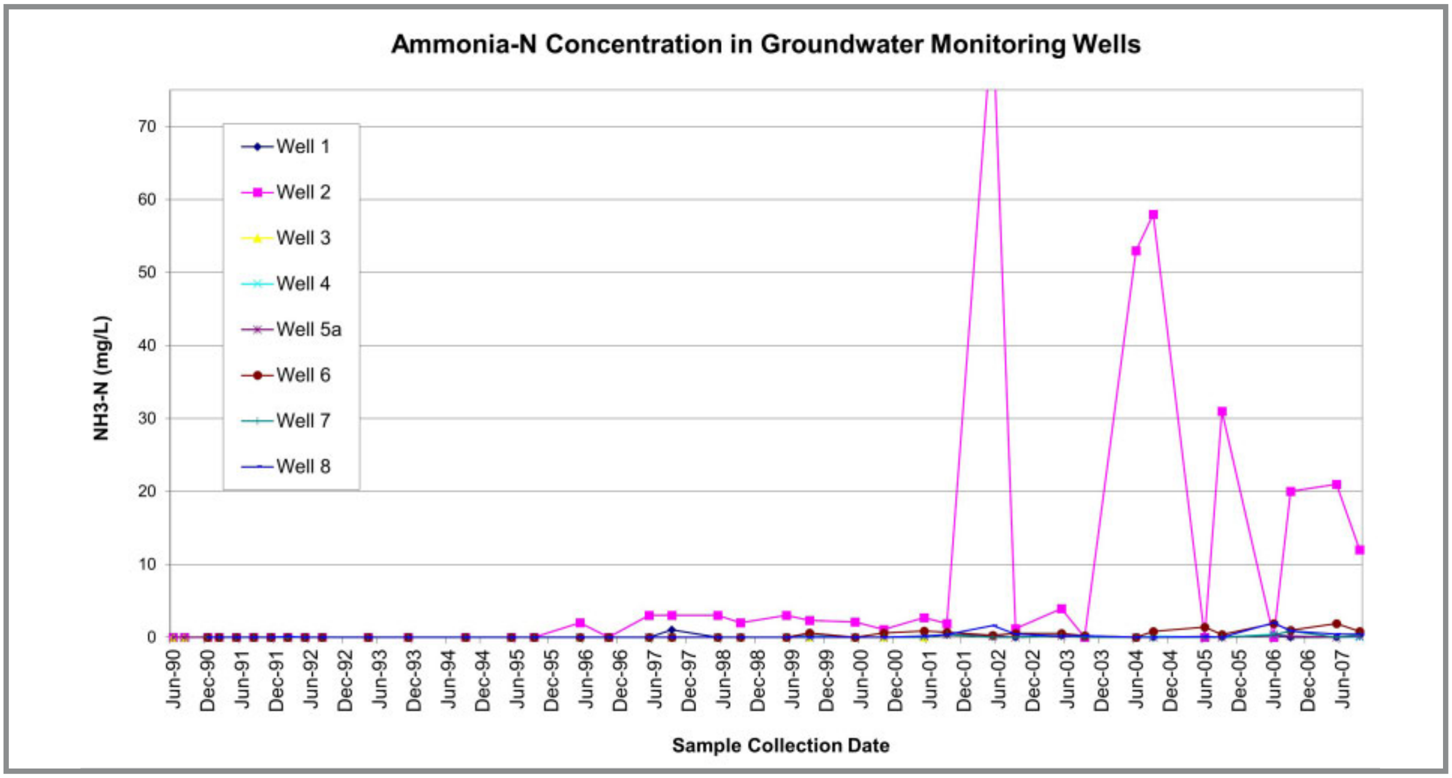

Figure 25. Ammonia values (mg/L NH_4-NH_3-N) for each of the eight monitoring wells with scale truncated at the Blue Plains effluent limit of 6.5 mg/L.

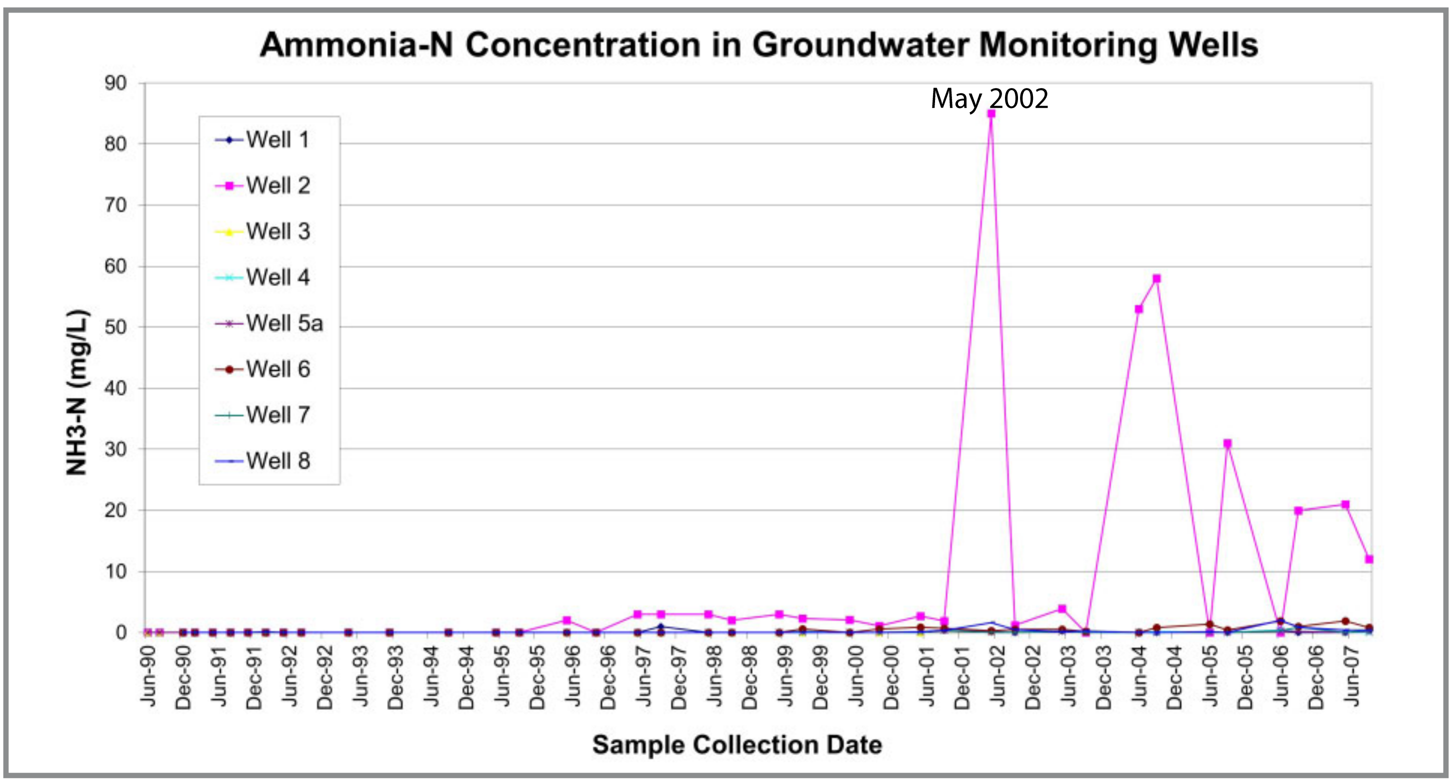

Figure 26. Ammonia values (mg/L NH_4-NH_3-N) for each of the eight monitoring wells (in full scale).

"For wells associated with historical analytical results, i. i.e., prior to initiation of the GSWMP: Wells MW-1, MW-4, MW-5A, MW-6, MW-7, and MW-8; it appears that results of the July 2014 round of sampling were generally consistent with previous results–as discussed in the First Semi-Annual Monitoring Report, i.e., Reviewed analytical results, for parameters associated with a USEPA primary drinking water MCL, were generally not detected or were detected below MCLs. Exceptions appear to be episodic and not persistent throughout the historic monitoring period."

GTA stated "… there were no detections of cadmium or nitrate (or lead or arsenic) above USEPA MCLs in the relatively deep wells at the site which are completed in and communicate with the Calvert Formation."

Based on the results of this additional evaluation, the results of our 2012-2014 monitoring at the site, and our review of historical site water quality data, it appears that cadmium and nitrate constituents that may be present in shallow groundwater within the Pliocene Upland Deposits remnants and spoils at the site are isolated from deeper groundwater systems. Based on the results of our additional evaluation, it appears very unlikely that groundwater constituents that may exceed EPA MCLs at the site would impact drinking water supplies. This conclusion is based on the results of our evaluation including the following: no detections above EPA MCLs in deep wells at the site; a 150- to 300-foot thick confining unit (MGS, 1990) that vertically isolates/separates groundwater beneath the site from deeper confined aquifers that may supply water to wells; and most of the residential areas in the immediate vicinity of the site are served by the public water supply system.

Based on the results of this additional evaluation, as well as the results of GTA's semiannual monitoring performed during the three-year period of 2012-2014, and our review of previous on-site monitoring results for the 19-year period of 1988-2006, it appears that constituents detected in groundwater at the site are not adversely influencing aquatic life conditions in Burch Branch, or drinking water supplies in the site area. Section 4.0 of the GTA's semiannual monitoring report supported this conclusion. The 22-year record of water quality monitoring (1988-2006 and 2012-2014) appears more than sufficient to characterize water quality conditions at the site. Based on our review of the extensive record of previous monitoring data for the site, and based on the results of this additional evaluation, it appears very unlikely that groundwater constituents detected at the site would adversely influence area drinking water supplies or aquatic life in Burch Branch in the future.

Summary

Whether monitoring for research or regulatory purposes, the magnitude of the work is a limiting factor. Without heavy excavation equipment and trained operators, researchers cannot install monitoring systems on DRE land.

Tools for monitoring include wells, drain lines, suction lysimeters, and pan lysimeters. You must understand and target the type of flow (saturated or unsaturated) that you want to capture.

Installation of monitoring sites starts with geological knowledge of the site. Installation can be dangerous, mostly from trench collapse. While no two sites are the same they can usually be broadly classified as granular porous media, broken rock mine spoil, or rock. DRE would not be considered for rock, so it won't be discussed further. There are several options for monitoring granular media. While there are several approaches for monitoring broken rock, they are more difficult, more expensive, more prone to error, and less flexible than monitoring granular media.

The problems with monitoring broken rock include the difficulty and expense of drilling a well, the difficulty and danger of digging a trench to put a drain tube in, the difficulty in determining where, on the surface, water might have originated, whether it passed through the contaminant of interest, how fast the water flowed, and other parameters dealing with the unsaturated flow of water through broken rock. Monitoring to meet regulations sometimes specifies wells, which can lead to difficulties in both well installation and interpretation of results.

Monitoring porous media spoil is inherently more representative than monitoring broken rock spoil. Monitoring porous media is mostly used for monitoring constituent concentrations because mass flow quantification requires a considerable amount of effort and funds to measure water flow rates through porous media. Monitoring broken rock spoil can provide fair results if the focus is near-surface (Kostyanovsky, et al., 2011a, Kostyanovsky, et al., 2011b, Kostyanovsky, et al., 2011c) but monitoring constituent movement at the water table interface has an unknown amount of uncertainty associated with the results.

Knowledge of the nitrogen cycle is valuable to identify physical location for samplers and the types of analysis. Of course, the same knowledge is essential to understand and explain what the fate of the contaminant might be. Foliar leaf monitoring and biosolids pack monitoring might be required by a regulatory agency and might also be useful in understanding how to manage and when to harvest the trees.

Comprehensive understanding of the DRE system requires multiple disciplines; plant physiology and forestry; surface and groundwater hydrology; and all manner of soil science (soil microbiology, fertility, soil physics, and soil chemistry). This understanding is necessary to design an appropriate monitoring system and correctly interpret monitoring results.

Opportunities for DRE in Maryland

There are more than 10,000 acres of sand and gravel mine spoils in southern Maryland (Table 4) that have a deep underlying clay layer similar to the ERCO site. The clay layers in St. Mary's County range from 12 to 40 feet thick and are located from three to 62 feet from the surface. Sand and clay layers are interbedded in the upper portion of the Potomac Group in Prince Georges County. Along the Western Shore, clay ranges from a few feet to 100 feet thick with exposed layers going from older to younger–north to south. When all this clay is combined with the growth of nitrogen demanding hybrid poplar trees, a natural recycling system will occur that will utilize nutrients on-site, produce forest products, generate wildlife habitat, and reduce erosion while reclaiming abandoned, biologically dead soils created by sand and gravel surface mining operations.

Table 4. MD DNR Water Administration, 1998

County in Maryland	Number of Acres
Prince Georges	5,887
Charles	3,132
Anne Arundel	2,693
Baltimore	1,076
Total	**12,788**

Why Not Use Native Trees Instead of Hybrid Poplar?

The hybrid poplar clone used at ERCO occurs naturally in the Mississippi river valley but is not native to Maryland. Most native tree species are unable to survive and grow in the hostile environment of a mine spoil and are very conservative in their use of nitrogen compared to hybrid poplar. A 1998 two-year study at the ERCO site planted red maple, black walnut, tulip poplar, and American sycamore bare root seedlings along with hybrid poplar cuttings (known as steckings) on a prepared DRE entrenchment site. After two years. the hybrid poplar cuttings were well established, but American sycamore was the only native hardwood to survive and grow. However, height growth was only half that of hybrid poplar. The hardiness of sycamore under harsh growing conditions is demonstrated in other studies but it uses small amounts of nitrogen compared to hybrid poplar, which would significantly reduce the biosolids application rate in DRE.

Benefits of Using Hybrid Poplar

Poplar is the general term for trees in the genus *Populus*. The genus includes Lombardy poplar, black cottonwood, eastern cottonwood, and aspen. Several clones are produced when plants of different varieties and sometimes species are cross-bred. Many different clones have been developed over the years for commercial purposes and go by the names of DN-11 or OP-367, to name a few. Different clones vary in their growth characteristics, insect and disease resistance, and other characteristics depending on the site. It is important to perform clonal trials prior to large scale planting to assure the clone chosen expresses desirable characteristics on the site being considered. Clonal trials were run at the ERCO site (Figure 27) for six years and OP-367 was best suited for this site.

The clone used until year 2000 was HP-308, but problems with cottonwood beetle, slow growth, and the changing makeup of biosolids required experimentation with new clones. After 6 years, OP-367 was the best performer in terms of survival (96%) and total height growth (30.5 feet). DN17 had good total height growth (27.2 feet) but poor survival (47%). OP-367 has been the clone of choice for all future plantings at ERCO and mine spoil locations in Pennsylvania and Ohio.

For use in the DRE system, hybrid poplars have numerous benefits:

- Hybrid poplar is well researched and well understood. Known as a short rotation forest crop, hybrid poplar has been planted for commercial pulp production in the Pacific Northwest for decades and utilized in agroforestry planting throughout the US.

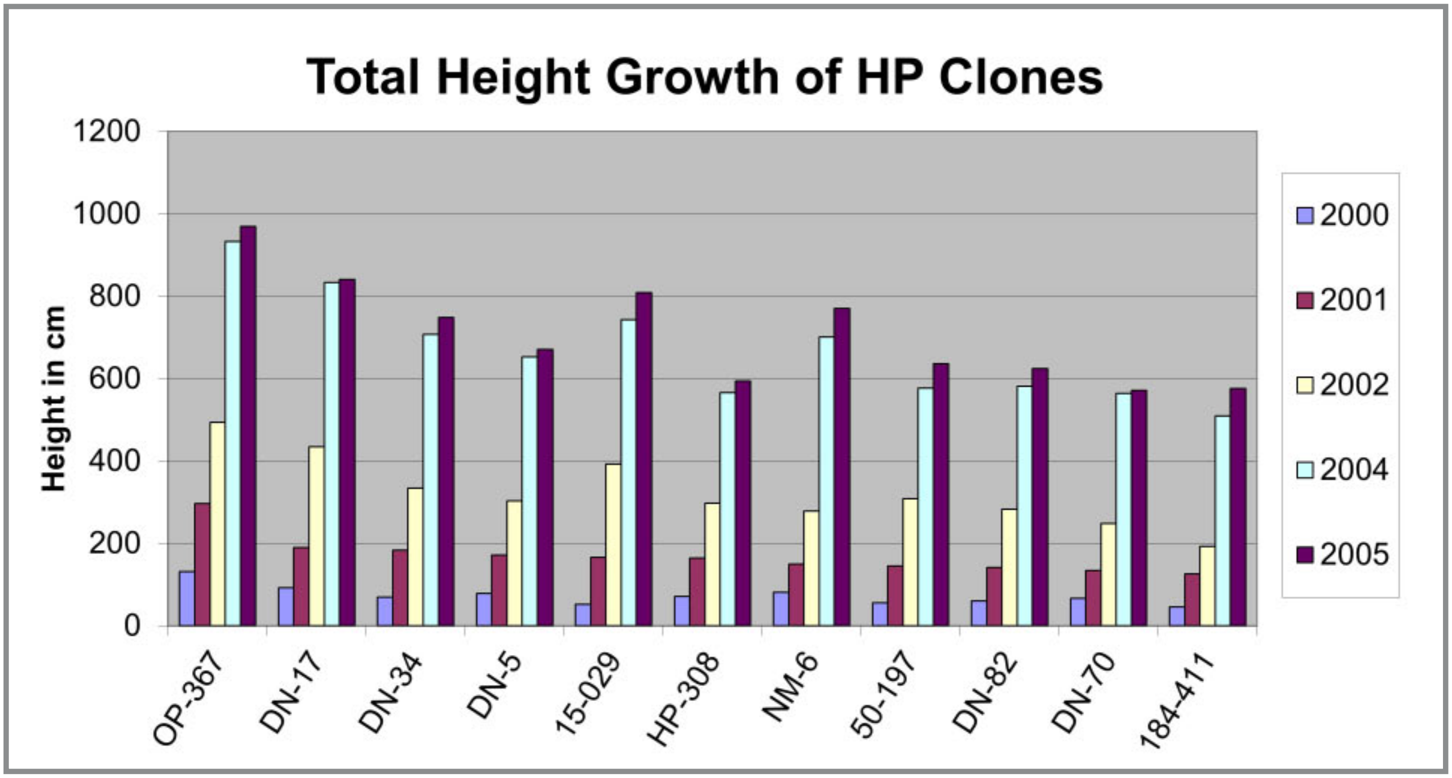

Figure 27. A trial of different hybrid poplar clones at the ERCO site in Maryland found clone OP-367 to be the best performer based on survival and growth the first five years.

- Hybrid poplar has been planted along riparian buffers in the Midwest to uptake nitrogen flowing from farm fields and stop it from reaching waterways, which is similar to one of the goals of the DRE system.
- Hybrid poplar is used regularly in phytoremediation projects to draw contaminants from groundwater. To sustain growth, the deep roots remove large amounts of water which includes the contaminants in the groundwater.
- Hybrid poplars are fast-growing trees and, unlike many native trees that are very conservative in their use of water and nutrients, hybrid poplar can be thought of as a water pump capable of utilizing what is available and producing deep roots to find additional sources of water and nutrients.
- Hybrid poplar can thrive in heavier textured soils such as clay and can grow in waterlogged conditions. Many species capable of growing in waterlogged soils have developed *aerenchyma* cells, which are air-filled cavities that provide an internal pathway for the exchange of oxygen and other gases between the plant organs above the water and submerged tissues. In the case of hybrid poplar, oxygen transported through the *aerenchyma* cells passes through the root pores into the surrounding biosolids pack, enabling mineralization of organic N to nitrate that can be taken up by roots to sustain tree growth.
- Hybrid poplar produces large amounts of root biomass and can turnover in 30 days. This creates a large component of organic matter. This leads to both soil improvement and carbon sequestration.
- Hybrid poplars have a high nitrogen demand. Most native tree species may use anywhere from 20–60 lbs. of N/acre/yr., but hybrid poplar is capable of utilizing at least 360 lbs. N per year per acre, with even higher rates of utilization reported in some research studies. As a result, the DRE system can utilize a reasonably high biosolids load without loss of N to the groundwater.
- The rapid growth rate of hybrid poplar allows it to be harvested in short rotations of five to 10 years, with longer rotations if desired. This provides for economic options in agroforestry systems that require cash flow in a reasonable time period.

DRE Used Elsewhere

The DRE pioneered by ERCO on spent gravel mines in Maryland has been adapted and used to reclaim coal mine spoil sites in Pennsylvania and Ohio, and another

Figure 28. Deep row on coal mine lands present more challenges due to the large rocks. The deep rows may or may not be graded depen15ng on the site (left). The trees on the right have reclaimed the site which was mined before reclamation was required. DRE provides many environmental benefits for water quality, wildlife, etc.

metal mine site in British Columbia. South Africa has also applied DRE to beneficially utilize biosolids from a wastewater treatment plant. U.S. coal mine land reclaimed using DRE were mined before the Surface Mining Control and Reclamation Act of 1977, which requires regrading and stabilizing the surface with grass or other vegetation. Thousands of acres of land mined prior to 1977 remains unreclaimed and the landowners have no legal obligation to complete any reclamation. Most of the mine sites are devoid of vegetation or barely able to maintain forest cover that provides wildlife habitat and protection from erosion.

DRE provides an economically viable reclamation method that combines an upfront income from the tipping fee received when the biosolids are delivered, along with the income or value of the wood produced at the end of the tree rotation. It transforms old mine spoils into land that provides numerous environmental benefits, without government subsidy, into income-producing properties that provide jobs, and a beneficial way to utilize biosolids. DRE adds organic matter to sterile soils and provides the possibility of creating soil capable of sustaining productive tree cover (Figure 28).

Nutrient Sacrifice Concept/Philosophy

Biosolids applied to granular soils/spoils that have sufficient soil fines (clay) to inhibit water flow, create anaerobic conditions in the biosolids pack, and have hybrid poplars established to take up nutrients do not, according to our research, leach nitrogen. This is the common condition on sand and gravel mine sites on the western edge of the coastal plains in Maryland.

Using DRE on coarse particle soils/spoils results in nutrient loss (Kostyanovski et al., 2011). Establishing a sustainable cover using DRE on coarse textured soils/spoils will most likely leach nitrogen in the early part of the DRE cycle. This nitrogen loss is viewed by some as a necessary sacrifice to revegetate and reduce erosion. Hence, DRE has been applied to broken rock strip mine spoils. Many coal mine sites have problems with acid mine drainage, lack of vegetative cover, and severe runoff and erosion. For these sites, some nitrate loss may be an acceptable cost for the benefits of the DRE system.

Operational DRE Sites

The University of Maryland research project was completed in cooperation with ERCO, Inc. and lasted from 2002-2007 and provided verification that water quality was not negatively impacted by the DRE technique when used on sites with clay components in the soil. Groundwater wells up and down gradient of the ERCO parcel did not show significant nitrate pollution from 1982 until when final site closure occurred in 2014. MDE has not permitted additional operations, but other organizations in other states and countries have. This led to development of DRE research projects and commercial operations that have been permitted in the following locations, most of which are coal mine sites.

The major difference between the ERCO site and many coal mine operations is the high clay content of gravel mine sites represented by ERCO and the rocky and looser soils representative of coal mines. DRE is a system that was developed on clay and depends on the clay to maintain the anaerobic nature of the buried biosolids. A brief description of each project and an information source is provided.

Figure 29. Sign at the ERCO Beneficial Use Tree Farm started in 1981 in Brandywine, MD where the Deep Row Entrenchment (DRE) technique was developed and researched.

- **ERCO, Inc. Tree Farm, Brandywine, MD. [Research & Commercial].**
  Mr. Paul Flamino started ERCO, Inc. in 1981 and is credited with developing the concept of DRE using hybrid poplar trees (Figure 29). He contracted a consultant to analyze existing trenching and hybrid poplar research to develop a nitrogen budget for growing hybrid poplar on a 100-acre abandoned and eroded gravel spoil using a one-time application of biosolids that would sustain tree growth for five to seven years. The research permit to start applications at the ERCO site was first issued by the Maryland Department of Environment in 1982. Over the years, his sons Eric and Scott Flamino took over the enterprise and in 1999 brought in the University of Maryland, MDE, and Washington Suburban Sanitary Commission (WSSC) to fund targeted research to determine if water quality was negatively impacted using DRE. Almost $1 million was committed to research on a three-acre parcel heavily instrumented to measure water quality and tree growth.

  The soil water nitrate content was essentially zero for the first three years and increased to between one and 10 mg/l for the last four years, which is similar to that of a well-managed cornfield. The MDE would not acknowledge the research nor allow the development of other operations but instead required additional expensive monitoring from ERCO. In 2013, ERCO made the business decision to shut down the site leaving no viable DRE operation in Maryland.

  Relevant publications: Kays et al. (2006 a,b,c,d.e)

- **Reading Anthracite, Mahoney, PA. [Commercial].** The company started DRE experimental applications in 2005 using the UM research as the basis for the permit from the Pennsylvania Department of Environmental Protection Mining. The initial biosolids treatments were 60, 72, and 100 dry tons per acre, and extensive environmental monitoring was performed, including the use of wells, lysimeters, and drain tile collectors. The vigorous tree growth and lack of negative environmental impacts led to more planting and operational applications to extensive coal mine spoils owned by Reading Anthracite Coal Company. The permitted rate was 172 dry tons per acre. The lands receiving DRE are old coal mine spoils that were mined before the 1977 federal legislation required reclamation. Without the use of DRE it is unlikely the lands treated would ever be reclaimed.

  Relevant publication: Toffey et al. (2007).

- **Blackwood, Inc., Wind Gap, PA. [Commercial].** The lands treated were a combination of partially mined coal land that were mined before the 1977 federal legislation required reclamation, and some other land not mined. The permit for DRE was approved by the Pennsylvania Department of Environmental Protection Water Quality. The Reading and Blackwood sites are overseen by two different state regulatory agencies which has led to confusion. Over the course of four years (2012-2015) about 70 acres were treated. About 10 acres of DRE was completed on old mine spoil piles that were flattened out. Most of the DRE land was reclaimed using 172 dry tons per acre of biosolids, but some portions were applied with a rate of 250 dry tons per acres. The site preparation for DRE is unique, involved placing five feet of mixed overburden on top of old coal slag and rock. The deep rows are dug three feet deep into this constructed medium, leaving two feet below to filter anything coming from the trenches. The Blackwood site houses a Class A biosolids composting facility and other ventures. It is unclear if a permit will be sought for additional acres to be applied.

- **Blackwood, Inc., Wind Gap, PA. [Research].** In 2015, Penn State initiated a DRE study on a four acre mineland site in Schuylkill County, PA. The objective was to monitor the fate and transport of the biosolids nitrogen and track the establishment and initial growth of the hybrid poplars. Class B biosolids were applied in trenches at 171 dry tons per acre. After one year, water samples from lysimeters and groundwater monitoring wells found nitrate levels below detection. Biosolid samples pulled six to seven months after entrenchment found N content had been reduced. It was concluded that most of the nitrogen lost was in the form of ammonia volatilization during the stabilization process. Erosion of the soil surface was a problem and pointed to the need for soil surface management plan that included some amendment with lime and vegetation. Due to lack of funding the study was not continued past the initial one year.

Relevant publication: Gogno (2015)

- **City of Columbus Wastewater Treatment Authority, Columbus, OH. [Commercial]**
In 2006, Columbus, Ohio initiated a Green Principles program for policy and decisions. The promotion of waste management strategies was one of six key principles and led to the initiation of beneficial reuse options for biosolids including: composting to produce Class A biosolids, waste to energy production, liquid land applications, and DRE. In 2013, the City of Columbus WWTA contracted with Ohio Mulch to implement DRE on a 1,000-acre strip mine (Figure 30). The contract called for 30,000 wet tons per year of Class B dewatered cake biosolids to be applied using DRE. The Maryland research from the ERCO site was used as the basis for the permit. In 2016 a second DRE permit was granted to Quazar Energy. A few details on each operation are provided.

Figure 30. Four year old hybrid poplar on coal mine spoils near Columbus, OH.

  - The *New Lexington Tree Farm*, owned by Ohio Mulch, received the first permit in 2013 and started making applications in 2014 at a rate of 170 dry tons per acre. The rate was increased to 340 dry tons per acre in 2016. The lands treated are old coal mine spoils that were mined before the 1977 federal legislation required reclamation.
  - The *Ohio Grow Tree Farm*, owned by Quazar Energy, received a permit in 2016 to do DRE at a rate of 340 dry tons per acre. The lands treated are old coal mine spoils that were mined before the 1977 federal legislation required reclamation.

Relevant publication: Fox (2014).

- **BC Ministry of Environment, British Columbia, Canada. [Commercial].**
British Columbia has accepted DRE as an acceptable practice and it is described in the following publication.

Relevant publication: SYLVIS Environmental (2008).

- **Similco Mine, Princeton, British Columbia, Canada [Commercial].**
Smelter Lake is the former tailings pond for the Similco Mine. The site lacks water due to an arid climate and wind-caused erosion of the tailings which impacts adjacent ecosystems. The surface application of biosolids to promote vegetation growth would not work on this site due to the wind erosion so DRE was identified as the method to facilitate reclamation efforts. SYLVIS, Inc., (www.sylvis.com) is a company with decades of experience in mine reclamation using surface application of biosolids and hybrid poplar trees. Mike VanHam, the president of SYLVIS, Inc. was instrumental in providing input into the Maryland DRE project at ERCO. SYLVIS completed the planning for the Smelter Lake reclamation program and made the necessary applications and establishment of trees. Only limited information is available on this project from SYLVIS, Inc. Those wanting more information should contact SYLVIS, Inc. at 427 Seventh Street, New Westminster, BC Canada V3M 3L2. (800) 778-1377.

Relevant publication: Deep Row Biosolids Application for Reclamation of the Smelter Lake Tailings Pond. https://www.sylvis.com/our-work/

deep-row-biosolids-application-reclamation-smelter-lake-tailings-pond

Figure 31. Deep row site ready for planting in South Africa. Image credit: Jay Bhagwan, Water Research Council, South Africa.

- **South Africa, Africa. [Research].**
  The University of KwaZulu Natal and Partners in Development used the DRE technique to determine if pit latrine and wastewater sludge from South Africa municipalities can be used as a fertilizer substitute for the agroforestry sector, and establish it as a safe and beneficial technique for sludge disposal. The country is developing policies and regulations for sludge utilization that moves away from landfill disposal. The research used eucalyptus trees instead of hybrid poplar trees due to the local climatic conditions (Figure 31). Initial results were very encouraging with nitrate remaining within acceptable ranges and tree growth significantly increasing using DRE.

  Relevant publication: Still et al. (2012).

- **Mineral Sands Mine Reclamation Site, Dinwiddie County, VA. [Research].**
  In 2006, Virginia Tech implemented a research project to better understand the impact of DRE and fertilizer treatments on a mine site that was completely composed of coarse-textured sand, with no clay component. The major interest was to assess the leaching of nitrate from the trenches. Close to 90% of the DRE nitrogen lost from biosolids was unaccounted for and either lost to denitrification as N_2, ammonia volatilization, or leached into groundwater unaccounted for by zero tension lysimeters. The final conclusion is that DRE should not be used for mine reclamation on coarse-textured media because the anaerobic conditions required to limit mineralization and nitrification cannot be maintained in such permeable soils. The research study also found there was no significant leaching of phosphorous, even in the coarse textured soils. The high binding capacity in the biosolids limits P solubility and transport.

  Relevant publication: Kostyanovsky, et al. (2011a, 2011b, 2011c).

Amending DRE with Surface Biosolids Application

The surface application of biosolids is permitted differently than DRE, resulting in an either/or choice between the two. A one-time surface application of biosolids to mine spoils provide nutrients for grass establishment during reclamation is permitted in many states at rates of 50-60 wet tons per acre.

Ohio and Pennsylvania are permitting DRE on some mine sites but it also is a one-time application rate, typically 171-342 dry tons per acre (Figure 32). The extensive nature of the mine spoils and the difficulty of reapplication due to rock and site issues, makes it likely that harvest and reapplication using DRE may be many years in the future.

The problem arises that operationally, a surface application of biosolids after DRE would be very beneficial to helping to encourage rapid surface establishment of vegetation to minimize erosion and keeping some surface moisture on site during the first year after spring or fall planting. The nature of mine

Figure 32.Rooted cutting planted in the fall on an Ohio coal mine spoil. A surface application of biosolids may be helpful in reducing erosion and hastening establishment of surface vegetation.

Figure 33. Surface application of biosolids after 5-7 years would help to sustain diameter growth of hybrid poplar trees and produce more valuable products.

Figure 34. Man is standing with back leg in depression caused by biosolid loss. This topography makes water runoff extremely unlikely.

spoils soils makes them very susceptible to erosion after fall and spring tree planting, as seen in Figure 32. The problem is compounded if moisture is lacking the first growing season, leading to moisture stress and possible high mortality. A layer of organic matter in the form of biosolids would help to keep moisture in upper soil layers and enhance survival and growth, the same effect provided by traditional surface application on mine spoils (Figure 33). At the same time, a surface application of biosolids would re-introduce the problem of offsite odor.

As hybrid poplar trees grow in the years after planting, a depression forms in the planting row (directly above the biosolids fill). The depression (Figure 34) is due to the tree roots drawing the moisture out of the biosolids pack. After two to three years, the trees utilize the majority of nutrients in the biosolids and tree growth stagnates and moisture and nutrient stress will result in mortality. Long- term growth of the hybrid poplar trees and other vegetation could be sustained for long periods of time if a surface application was allowed but present permit restrictions make this difficult. The depressions make it extremely unlikely that biosolids or the nitrate released by surface application would move offsite; rather they would settle into the depressions and rapidly be taken up for tree growth. The benefit of this practice would be to allow the production of larger diameter trees that are more cost-effective to harvest for forest products, such as wood chips, pulp, or small sawtimber. The common problem of odors would be minimal because mine spoils are typically located in remote regions and not near large population centers.

Educating regulators about the benefits of combining DRE and surface application to enhance the reclamation process and encourage longer harvest cycles, which will have multiple benefits for water quality, development of native forest, as well as economic considerations.

Best Practice for DRE Based on Operational Sites and Research Projects

Tree Planting–First Year Is the Best Chance for Planting Success

- **Site Preparation**–The process of burying biosolids for DRE loosens the soil and creates the best conditions for planting success, regardless of whether or not it is a coal or gravel spoil. The type of site preparation required after the soil settles will depend on whether or not the spoil is gravel or coal.

The gravel spoil representative of the ERCO site had a solid clay base.

- **Spring Planting**–The most desirable time to plant is early spring using cuttings that are about 1/2” in diameter and eight to10 inches long. Fall planting using rooted cuttings is being utilized on one DRE operation because labor is more available. However, there is a greater chance of desiccation, deer browsing, and soil compaction, resulting in low vigor in the spring when seedlings overwinter on a mine spoil. Spring planting allows for site preparation and DRE installation throughout the winter until the day of planting. In Maryland, fall planted steckings were squeezed up out of the ground by freeze-thaw cycles.
- **Proper Spacing**–Hybrid poplar is a short rotation woody crop and the option exists to alter tree density. Research and operational evidence has found a spacing of 10’ X 10’ (430 trees per acre) to be good standard to utilize, but it requires that 95% of the trees survive and growth. It is not advisable to plant extra trees based on the assumption that 20-30% will die in the harsh conditions found on mine spoils. It is best to develop a planting plan that does all the needed site preparation to assure planting success the first year. Some replanting the next spring may be needed but it usually is not as successful because of soil compaction and competition from other vegetation that has become established over the past year.
- **Planting on Trench or Between Trenches**–After the site has been trenched there is usually a characteristic uneven surface due to the overburden piled on top of the trenches. A study on a coal mine spoil has shown little difference between planting on top of the deep rows and between the rows. However, the best practice seems to be planting off to one side of the top of the pile.

  The ERCO site in Maryland had soils with little rock and the site was leveled before planting so the location of deep rows was not known. The cuttings were planted on a 10’ X 10’ grid with no concern for the trench locations and there was no obvious difference in the growth of the cuttings. Based on the available evidence there does not seem to be a difference on the rockier coal mine sites or the low rock clay soil sites found at the ERCO gravel mine.

  The opportunity exists on coal mine spoils with large variation in rock size and content to experiment with planting trees on the piled overburden of the trenches or between the trenches. Another option is to level off the piles and plant the entire site on a 10’ X 10’ grid.

Relevant publications: Kays et al. (2006d).

- **Planting Depth**–Using a planting bar or tool, plant the cutting so that one or two buds are above the soil surface. The buds will usually start to break open within a few days after spring planting and leaves will emerge within a week or two, depending on the weather. If any type of herbicide application is planned, it should be done immediately before the buds break or the cutting will likely be impacted. Read the herbicide label to understand potential impacts on planting stock.

Biosolids Entrenchment–Maintain Correct Overburden Depth

- **Depth of Overburden**–Regardless of the width or depth of the trench used, the depth of overburden will usually be about 16-24 inches. Deeper overburden makes it difficult for the hybrid poplar cuttings to reach the biosolids pack within the first year and obtain nutrients and moisture that is essential for growth and development.
- **Trench Depth**–Trenches should extend no deeper than four feet from the surface. Deeper trenches make it very difficult for tree roots to colonize around the trench. If a choice exists it is better to keep the trench depth closer to three feet if possible.
- **Depth to water table** should be at least three feet from the bottom of the deepest trench
- **Trench Along Contour**–Trenching should be along the contour if the slope is over 5% so that the additional height of soil on the trenches will act to reduce water velocity and associated erosion. Coal mine soils are prone to washing and erosion.

Choice of Hybrid Poplar Clone Important

- **Use Proven Clones**–Utilize existing research to determine the best clone for the site. OP-367 has been a proven clone in hybrid poplar studies in Oregon, British Columbia, and Maryland. It has good survival and growth and has few insect and disease problems.

- **Clonal Trial Recommended**–If possible, a clonal trial testing a variety of hybrid poplar clones can be established to assess growth and survival.

Produce Your Own Cuttings for Cost Savings

- **Hybrid poplar cuttings**, known as steckings, can be purchased commercially or cut from areas that have trees established. Cuttings should be cut in February or March prior to spring planting from last year's branches that are no more than one inch in diameter. The branches should be cut into sections that range from eight to 10 inches long and not less than ½" in diameter. Put the cuttings in plastic bags in bundles of 50 so the cuttings do not dry out and store them in a cool location until they are planted.
- **Producing your own cuttings** can save large amounts of money. Commercial cuttings may have a moderate cost ($0.60 each) but overnight delivery is required and extremely expensive, making it very attractive to consider production of cutting internally.

Vegetation Management

- **Herbicide Use**–Forest herbicides have not been used extensively to control competing vegetation on mine spoils using DRE. However, they can be very effective in helping to assure survival and growth during the first growing season and for any replanting efforts. The lack of knowledge and experience with herbicide application and selection by site managers appears to be a common reason why there has been little experimentation. In most cases, the mine spoil is devoid of any vegetation after biosolids are applied in the deep rows. If hybrid poplar steckings are planted in early spring, they can usually keep above the competing vegetation that comes with spring growth. However, if rainfall is lacking the competing vegetation may overtop the trees and rob needed moisture during the critical first growing season after planting. Once the tree roots can access moisture from the biosolids they will usually thrive. Vegetation management at the ERCO site in Maryland was done using regular mowing but the uneven surface and rock characteristic of DRE on coal mine spoils makes mowing unusable.
- **Pre-Emergent Herbicide**–After biosolids are applied and covered in the deep rows, the ground is bare from heavy equipment use. When steckings are planted in the spring most sites would benefit from the application of pre-emergent herbicide. When applied by a sprayer immediately after planting and before buds break on the steckings, it will stop seeds from germinating. This will give the steckings many months before competing vegetation can start to grow and compete with the hybrid poplar. This type of application has not been utilized operationally so actual prescriptions for different site conditions need to be developed.
- **Replanting**–Applying forest herbicides is usually critical to assure survival and growth of steckings where the site has laid fallow for a year before planting or if the first year planting had such high mortality that replanting was necessary the next year. After one growing season on sites where competing vegetation is firmly established, steckings replanted without control of competing vegetation will likely fail. Depending on the site, hard to control and invasive species like cherry, Japanese knotweed, and others may become firmly established. At a minimum, spraying the tops of the deep rows to provide about three feet around each planted stecking is essential. It may be easier to spray the top of all the deep rows or the entire planting site if vegetation development will overtop the newly planted steckings. Another option is to mechanically remove vegetation from deep rows using an excavator or bulldozer.
- **Total Vegetation Control Herbicide**–If planting fails the first year and the site needs to be replanted, the vegetation that established the first growing season must be killed or survival and growth of the replanted steckings is unlikely. The use of a broad-spectrum non-selective herbicide would be recommended. Products such as glyphosate (Roundup), imazapyr (Arsenal), triclopyr (Garlon), and others may be appropriate, but the site manager should identify the vegetation to be controlled and select herbicides that will give needed control. It is essential to read the label to determine the weeds controlled by different herbicides.
- **Pesticide Certification**–The site manager or someone onsite needs to secure commercial forest pesticide certification for forest application to meet regulatory requirements and become more knowledgeable about the use of pesticides in general. The U.S. Department of Agriculture or university Extension Service in the state can provide

the details on how to get the needed manual and when and where the exam is offered. Most states require the licensee attend a training each year to secure credits for pesticide recertification. In this way those new to pesticide use can learn and apply the herbicides in a correct way. In general, the proper application for pesticides is always available by reading the label.

Insect and Disease Problems

A serious insect problem of hybrid poplar is the cottonwood leaf beetle (*Chrysomela scripta*). High infestation levels are capable of significantly reducing tree growth and can be controlled using an integrated pest management approach, which will include insecticide. Growing sites should be monitored starting in April and through September. Growers should be concerned about damage to the terminal leaders of trees in their second and third year of growth, when poplars are actively utilizing biosolids. Thinning of leaves on the terminal shoot of plants, especially in May and June, can be indicative of beetle damage. There are a number of pesticides that can be applied to control the problem before damage starts to impact tree growth. The following resources are provided for more information cottonwood leaf beetle and other insects and disease problem.

Relevant publications: USDA (1989), Carlson (2017).

Deer–A Cost of Doing Business

If deer are a problem or may be a problem in the future, the entire site should be fenced and considered a basic cost of doing business. The use of tree shelters has not worked well in experiments on the harsh and extremely hot environment conditions of a mine spoil. The heat generated in the tree shelter will usually kill the tree. Deer will seek out and heavily browse hybrid poplars in the mine environment that are lower than five feet in height. Bucks can also cause extensive rubbed damage to young trees during the fall rut. Deer can cause plantation failure and set back afforestation efforts by years. If deer pressure (damage) is high, a minimum of eight-foot fence (10 feet is better) is required to physically stop deer. In this case it should be considered the price of doing business and be part of the business plan. Make sure the fence is located so that there are adequate and accessible gates and turnarounds for equipment.

Relevant publication: Kays (2003).

Figure 35. Harvested trees waiting for processing.

Irrigation–Have a Backup Plan

Adequate water during the first growing season is essential for the cuttings to grow and establish a root base in harsh mine spoil sites. It is impossible to know if adequate moisture will be forthcoming and a spring or summer drought after planting can result in unacceptable mortality and the need for replanting the next year. It is advisable to plan for supplemental watering during the first spring and summer after planting if natural rainfall does not occur. Options include sprinkler irrigation, trickle irrigation, or water application from a truck. Sprinkler irrigation has a lower capital investment and is more forgiving of impurities in the water. Trickle irrigation uses much less water and irrigates only the trees, not the weeds.

Biomass Production

The DRE system can utilize high application rates of biosolids because nitrogen mineralized is quickly taken up by hybrid poplar roots and converted to woody biomass at a faster rate compared to native trees. However, woody biomass production per acre assumes adequate stocking of trees to access all the biosolids. To have adequate stocking, the recommended planting spacing of 10 feet by 10 feet should have a minimum survival of 95% after one year. Experience at the ERCO site and coal mine spoils found replanting the second year is less successful due to compaction of the soil and competition by other vegetation. Herbicides to control undesirable vegetation the first year in hybrid poplar plantings have not been widely used but are essential to control aggressive invasive species and natural plant species that will quickly compete for resources. This is especially true on coal mine sites where mowing in not an option. Replanting the second year to address high mortality without adequate control of competing vegetation using herbicides or mechanical techniques has not proven operationally successful.

Estimating biomass per acre is determined by using field measurements of simple variables like diameter breast height (DBH - 4.5 feet or 1.3 meters from the ground) and total tree height to develop reliable equations. At the ERCO site, destructive sampling was done on hybrid poplar tree plantations from two to six years old of clone OP-367 (Felix, et. al, 2008) to develop equations to predict above ground biomass for individual trees specific to the DRE technique. Two equations were developed to estimate tree biomass for trees less than 4 cm DBH and trees greater than or equal to 4 cm (Table 5). Using accepted area sampling techniques, the total biomass per acre or hectare can be estimated.

Table 5. Biomass equation for individual hybrid poplar trees 2-6 years old using the deep-row entrenchment technique at the ERCO site (from Felix et al., 2008).

Diameter Breast Height (cm)	Biomass Equation
Greater than or equal to 4 cm.	Dry Woody Biomass (kg) = 2.6 X DBH (cm) – 9.64
Less than 4 cm.	Dry Woody Biomass (kg) = 0.5 X DBH (cm) – 0.35

Woody biomass equations developed by many researchers and businesses differ depending on the objective, clone, soil, climate, nutrition, and other factors. It is important to utilize equations appropriate for your area and clone, and it may be necessary to develop equations for that specific application. In the case of coal mine spoils with very different soils and environment, using the equations developed for the gravel mine at the ERCO site may not be applicable.

If a planting site fails to have adequate stocking due to poor survival or growth, the capability to utilize the nitrogen in the biosolids to produce woody biomass is compromised. This upsets the assumptions behind the DRE technique that balances nutrient inputs from the biosolids with potential uptake of available N and other nutrients. Site managers must carefully implement site preparation, planting techniques, and site maintenance to attain proper stocking levels essential to utilize DRE.

Relevant publications: Felix et al. (2008); Kays & Felton (2014).

Harvest of Trees

- One rationale for the planting of trees using a 10’X 10’ spacing is to allow for the use of commercial forest harvest equipment, such as feller/bunchers. Instead of having many small trees, the 10’X10’ spacing allows for a smaller number of larger trees. The average diameter of trees after five to seven years will usually not be more than five to six inches at 4.5 ft. from the ground. This wood is suitable for pulp, wood chips for heating, and mulch.
- Depending on the operation it may be that allowing someone to harvest the trees (Figure 35) and take the wood at no cost to the owner is a real benefit, versus having to pay someone to harvest the trees and remove them from the site. If there is enough acreage and the stocking in larger trees, mulch operators may be attracted to this type of arrangement.

Retrenching

The DRE operation at the ERCO site in Maryland was initially based on a nitrogen budget derived from research and operational experience. The two parameters to allow harvest and retrenching were:

1. 70% of biosolids in the trench was mineralized, and;
2. foliar percent N was less than 3.5%

Economics of DRE

DRE can be a profitable and sustainable business enterprise, especially for sand and gravel, coal, and metal mining companies that have extensive acreages of land that is taxed but has questionable value for other developmental or income-generating purposes. A major advantage of DRE is that the biosolids generator pays for DRE at the beginning of the operation so the landowner or business owner receives the majority of their income upfront and the promise of a forest biomass product at the end of a 5-8 year rotation. The ERCO site charged a tipping fee to WWTP’s for lime-stabilized biosolids to be placed in the deep rows.

The cost of trucking is a major factor that will impact the actual profit. However, the increasing difficulty of land applying biosolids will likely result in biosolids producers willing to pay reasonable trucking costs to DRE sites. Depending on the state or country, a permit must be obtained and the permit requirements for monitoring can be a major expense that must be understood before creating a business plan.

Figure 36. Harvesting of trees can be a major cost. Larger diameter trees increase the options for selling the wood and covering the harvesting cost.

The trees should be managed so the biomass harvested will pay for the harvesting cost, and ideally, provide a source of revenue. Managing the plantation to produce fewer trees of larger diameter will increase utilization options and reduce harvest cost (Figure 36).

Sustainable DRE operations may require perimeter fencing to stop deer browsing which can cause total plantation failure and upset harvest cycles and expectations. The availability of irrigation for the first year may be necessary in areas with inadequate rainfall.

An attempt was made to create a hypothetical business scenario for a DRE operation patterned after the ERCO project in Maryland. Financial projections were based on annual income and expenses for an operation that applied 172 dry tons per acre. The main expenses that change with the higher application rates are equipment operators, and bulldozer and excavator, and equipment costs. The bottom line of this analysis is the profit, calculated as annual income minus annual expenses.

At the lower application rate of 172 dry tons per acre the enterprise operated at a loss ($19,675); however, profits increase dramatically at the 340 dry tons per acre rate. The actual numbers for any operation will vary greatly but the general analysis clarifies that as application rate increases, profits will increase. This will likely attract others into the industry. It is important to note that the higher profits at the higher rates would not likely be sustained as more competitors entered the industry and market competition would likely reduce profits in the future.

Relevant publication: Kays et al. (2006d).

Foliar Leaf Monitoring

- **As hybrid poplar trees grow** they mineralize nitrogen in the biosolids and uptake it to grow leaves and biomass. It is recommended to test the leaf samples for %N, %P, and %K. The percent foliar nitrogen and phosphorus in the leaves provides a measure of how rapidly biosolids are being utilized and is correlated with biomass growth. Maximum growth of hybrid poplar under fertilized conditions is thought to occur at 3.5% foliar nitrogen and 0.42% foliar phosphorous. However, fast growth is known to occur at 2.5-3.5% foliar nitrogen and 0.25-0.40% foliar phosphorous. If % P levels are low compared to %N then the trees may respond to the addition of phosphorous fertilizer.
- **Foliar leaf sampling** is usually started in the second growing season. The timing and collection of leaf sample is critical to get an accurate measure of percent foliar N. The following protocol is recommended:
    - Sample time during the peak of the growing season–early to mid-August in Mid-Atlantic area.
    - Sample the first fully expanded leaf which is usually five to seven leaves down from the terminal leader. If you sample leaves that are still actively expanding, the leaf will be pulling nutrients from the tree and give unrealistic value. If the leaf is not expanding it will be a net exporter of nutrients and values may be low.
    - Sample at mid-day when actively growing.
    - Sample seven to 10 trees from each site and make a composite sample. To get a getter assessment across a site you can make a composite sample from three different areas. The average of the three samples will provide a reliable average across the site and possibly indicate any differences across the site.
    - Put all leaves in a paper bag and allow to dry in a well-ventilated area. When dry send to a lab for analysis. Analyze for TKN and phosphorous.

Relevant publication: VanHam, M. (2003). *Personal communication.*

Biosolids Monitoring

Annual sampling of biosolids pack at each site is important to follow the trend in mineralization of the biosolids pack. The operational research in Maryland was required by permit to randomly sample a trench location in each planting. A backhoe was used to dig a trench perpendicular to the chosen trench location and then a composite sample was taken from different locations in the trend. The sample was analyzed and when 70% of the biosolids were mineralized, the site could be harvested and reapplied as long as foliar percentage of N samples were under 3.5% N.

The threshold of 70% mineralization was sourced from the research by Taylor et al. (1978). The research actually measured total N loss from the biosolids which could come from denitrification and mineralization. At this point the biosolids are stable and could not lose any more N. The transition of the biosolids into the peat stage comes before the 70% loss.

At 70% the biosolids pack is very thin and small and sampling of the pack is only needed if the objective is to reapply or if there is a bond release predicated on reaching the 70% mineralization threshold.

Education and Outreach

- The history of DRE research at the ERCO site in Maryland and subsequent application of the technique in other states clearly demonstrates the difficulty of regulators and other well-meaning citizens to understand basic biological concepts, how trees grow, and their utilization of nitrogen. The original ERCO research incorporated the use of annual field days, fact sheets and other outreach tools to explain that hybrid poplar trees actively converted organic nitrogen in biosolids to nitrate in a closed system to sustain tree growth and biomass accumulation. Even with these efforts regulators appear to believe that the nitrogen in biosolids used in DRE is still present in the ground and fear that they will be converted to nitrate and impact water quality.
- Continuing education and outreach through well-planned programs can help to break this barrier but it will require constant effort (Figure 37). Many DRE operations are controlled by engineers and other business entities that do not have the forestry experience needed to assure the system operates properly. Organizations and landowners faced with the challenge of educating regulators should engage university extension professionals or other credible organizations for educational assistance.

Relevant publications: Two graduate studies were completed at the ERCO site, and the theses produced from the studies are Buswell (2006) and Maimone (2012).

Figure 37.Education workshops for regulators, policymakers, and natural resource professionals is essential to better understand the DRE technique and life cycle.

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