Soil characteristics and their role in developing conditions favorable for denitrification

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Abstract
The use of riparian buffers and controlled drainage to reduce nitrate-nitrogen in groundwater has been documented in many field studies. Denitrification is the mechanism attributed to nitrate losses. For these Best Management Practices to effectively remove nitrate from groundwater, conditions must be favourable for denitrification. Critical factors for this biological transformation to occur include the presence of nitrate, a source of carbon, a favourable pH, and an appropriate range in temperature. Soil redox potential is an indicator that provides evidence as to whether or not nitrate reduction would occur. This research was conducted on four riparian buffers, each with five vegetative treatments, in order to determine if these factors were present and if so, if they were within the range required for denitrification. In addition, the effect of soil texture and its relationship to these factors was also studied. Soil texture had an influence on soil redox potential. Sandy textured soils generally had redox values too high for denitrification, while clayey textured soils provided lower redox values that were within the range for this biological transformation. Carbon was located at all locations on the buffers. While it generally was accumulated in the surface horizons, soil carbon content was also measurable at greater depths, especially where soils were sandy textured. Soil nitrate was also found deeper in the soil profile where soils were higher in sand content, which is a result of leaching. Soil nitrate patterns were similar. Soil temperature and soil pH did not appear to be limiting factors at the research site.

Key Words
Soil redox, soil texture, nitrate, soil carbon, riparian buffer, controlled drainage.

Introduction
Research efforts during the last several years have contributed to the knowledge that riparian buffers effectively remove pollutants, specifically nitrate-nitrogen from groundwater (Jacobs and Gilliam 1985; Lowrance *et al.* 1985; Jordon *et al.* 1993; Gilliam 1994). Nitrate-nitrogen is customarily found in groundwater in Eastern North Carolina as a result of agricultural practices and is affected by soil type and hydrology (Spalding *et al.* 1993). In recent years, efforts have been undertaken to reduce the amount of nitrate-nitrogen moving into groundwater and subsequently, to surface waters. Riparian buffers are commonly narrow forested or grassy areas located along small streams and rivers. Laterally flowing groundwater, frequently flowing above a restrictive layer located in the soil profile, flows into the riparian zone, which are generally characterized as having poorly drained soils. Denitrification, a major pathway through which nitrate-nitrogen is removed, occurs in this zone. However, the presence of nitrate in a saturated soil does not ensure denitrification. Other factors, i.e., amount and presence of organic matter, pH, the presence of denitrifying microorganisms, and soil temperature influence the occurrence of this biological reduction. Oxidation-reduction reactions occur as oxygen becomes limiting. In the absence of oxygen, anaerobic bacteria use other oxidized species as electron acceptors in a stepwise order. Nitrate becomes the electron acceptor upon the disappearance of oxygen, followed by MnO_2, $Fe(OH)_3$, SO_4^{2-}, and CO_2. Organic matter must be present for these oxidation-reactions to occur, as it is the energy source for anaerobic bacteria. A review of nitrate removal in stream riparian zones by Hill (1996) suggested the importance of a continuous supply of carbon as an energy source for denitrifying bacteria that further indicates the significance of the link between vegetation and denitrification. The ability of a soil to retain water or reduce its flow (permeability) is influenced by soil texture. Coarse textured soils have little structure, large pores, and permit rapid flow of water. In contrast, fine-textured soils have small pores due to aggregation and retard the transmission of water. This influences conditions that are required for denitrification, such as whether or not the oxygen status is high or low (saturated soil). Nitrate-nitrogen, which is of great concern with regard to water quality, is highly mobile and easily leached. Smith and Cassel (1991) estimated the

nitrate leaching ability of soil materials. They noted four aids in estimating nitrate leaching, which included permeability, available water-holding capacity, hydrologic group, and leaching class. Leaching class is based on soil texture. Soils that have a sandy texture are expected to have leaching losses in most years, while the finer textured soils, such as clays, will have insignificant losses. Texture is also an important element in decisions regarding the use of water table management. Soil permeability is the most important soil factor in determining the effective use of controlled drainage, a practice that has been shown to be useful in reducing the amount of N through reduced flow and higher denitrification rates due to favorable conditions provided by a higher water table (Doty *et al.* 1986). Megonigal *et al.* (1993) studied the effects of soil texture and relative positions of soil-forming processes. They showed that oxygen content and redox potential generally decreased with depth, except where a perched water table was present and concluded that soils with a high clay content reduce oxygen diffusion rates, resulting in sub-atmospheric oxygen levels even where soil was not saturated. Understanding the processes and factors that control the effectiveness of riparian buffers, as well as controlled drainage, are critical in determining where these practices will work. Redox potential is a good indicator of whether or not conditions are suitable for denitrification.

Methods

Soils investigations for this research study were conducted on buffers located at the Center for Environmental Farming Systems in Goldsboro, North Carolina. Several buffers, in conjunction with controlled drainage, were established along channelized drainage ways for the purpose of evaluating their use in reducing nonpoint source nutrients on water quality in the Neuse River. The site is geologically complex due to its location next to the Neuse River, which is subject to flooding. The soils are terrace and floodplain soils. Recent soil mapping by soil scientists from the government and private sector identify the soils of great extent at this site as Roanoke (fine, mixed, semiactive, thermic Typic Endoaquults), Tomotley (fine-loamy, mixed thermic Typic Endoaquults), Tarboro (mixed, thermic Typic Udipsamments), and Wickham (fine-loamy, thermic Typic Hapludults). However, soil maps are developed at a scale which permits inclusions of other soils and therefore, for site specific work, a soil investigation is required. During the installation of thermocouples on the site, soils were excavated to a depth of 152-cm using a hand auger. During the excavation, the soil was removed from the auger, the depth recorded, and the soil was carefully placed on a plastic sheet in the order in which it was removed. The entire 152-cm profile was described, photographed, and sampled (by horizon) for analysis, which included nitrate-nitrogen, total carbon, pH, and particle size. To easily compare soil profiles located at the ditch and field edges of each of the buffers, soil textures are divided into three group, i.e., sandy, loamy, and clayey texture groups. Generally, the use and management of these soil groups are similar. The sandy textured soils include the sands and loamy sands, while the clayey textured group includes the clays. The loamy textured group was divided into two groups, the moderately coarse-textured or medium textured soil materials and the moderately fine-textured soil materials. The moderately coarse-textured or medium textured soil materials included coarse sandy loam, sandy loam, fine sandy loam, very fine sandy loam, loam, silt loam, and silt. The moderately fine-textured soil materials included clay loam, sandy clay loam, and silty clay loam (Soil Survey Division Staff, 1993). General observations about the research site, field Eh measurements, and soil carbon are reported. Nitrate trends and nitrate/chloride ratio patterns were also studied, but they are not reported in this paper.

Results

Soil texture

Soil profiles described on the buffer with no water control structure (R1) and the buffer with a water control structure present (R2), at both the ditch and field edges, contribute information about redox behavior in the soil. Generally, soil horizons of moderately fine-textured or clayey soil materials permitted water to be retained longer, resulting in lower redox potential values by essentially acting as a temporary restrictive layer within the soil profile. This was demonstrated frequently throughout the study period following rainfall events. Soils with moderately fine-textured or clayey horizons exhibited decreases in redox potential values for a brief period. Values rebounded as the oxygen status of these horizons increased. In contrast, soils with sandy horizons in the upper profile provided little water holding capacity and redox potential values remained high throughout the study. However, soils inundated by floodwaters, as a result of devastating hurricanes, behaved similarly with regard to redox potential, for a very short period, regardless of soil texture. This was based on the presence of water and not texture. Differences as to how rapidly soils recovered to their pre-hurricane status were related to soil texture.

Site R1 – ditch edge:
With one exception, soils were fairly uniform along the ditch edge. Soils were generally moderately coarse-textured and medium textured in the upper part, followed by moderately fine-textured or clayey soil materials, which were underlain by sandy soil materials. The exception lacked the moderately fine-textured or clayey soil material within its profile. Redox values at the 76-cm depth were generally above 500 mV throughout the study period, except for the period following inundation by hurricane flooding. One location had a clayey horizon higher in the soil profile as compared to the other three locations and exhibited a fluctuating Eh values following rainfall events. At 152 cm, all soils had sandy soil materials present. In addition, soil colors had a hue of 7.5 YR or 10YR, values of 5 to 7, and chromas of 3 to 8, indicating that reducing conditions were not present. Redox potential values at this depth ranged from 600 mV to 800 mV, which are consistent with non-reducing conditions. It is most likely that when groundwater was present at this depth, it was oxygenated. Hurricane flooding had little effect on Eh values at this depth.

Site R1 – field edge
Soil profiles at the field edge were markedly different from soils at the ditch edge. The most obvious difference is the presence of a clayey layer located within 40 to 80 cm of the soil surface. At 76 cm, Eh values tended to have more variability and behaved accordingly, to rainfall events. At 152 cm, all locations had sandy soil materials present. Soil Eh values, averaging approximately 700 mV, were similar to those at the same depth along the ditch edge with the exception of one location. One electrode at this site consistently had Eh values that hovered slightly above –100 mV. It is interesting, however, that at this location, Eh values decreased dramatically at the 76-cm depth due to a rainfall event, and increased substantially at the 152-cm depth as oxygen was likely moved deeper into the soil profile.

Site R2N – ditch and field edges
The soil profiles located along the ditch edge provide information as to how soil redox potential is affected by differences in soil texture on the same landscape position. Figure 1 illustrates differences between buffers and provides valuable information as to why there were noticeable contrasts in soil redox potential within buffers. The upper part of each soil profile uniformly consisted of moderately coarse-textured and medium-textured soil materials. However, the centre section of the buffer is different than locations at the ends of the buffer, i.e., Locations A, C, E, G, Y, J, K, and M. At the middle of the buffer, moderately fine-textured soil materials are present. Sandy soil materials at Locations G, W, and I dominate the lower part of the profile, while Locations E and J have moderately coarse-textured and medium textured soil materials. Locations K and M are underlain by moderately fine-textured soil materials. At the 76-cm depth, soil Eh values along the ditch edge averaged above 700 mV throughout the study period, decreasing temporarily following rainfall. Soil textures along the field edge were generally moderately coarse and sandy. Redox potential values averaging between 600 mV and 700 mV indicated the soils inability to retain water at this depth during periods following rainfall. It should also be noted that the water table averaged approximately 40 cm below the depth at which the electrodes were installed. Conditions favourable for denitrification were infrequent.

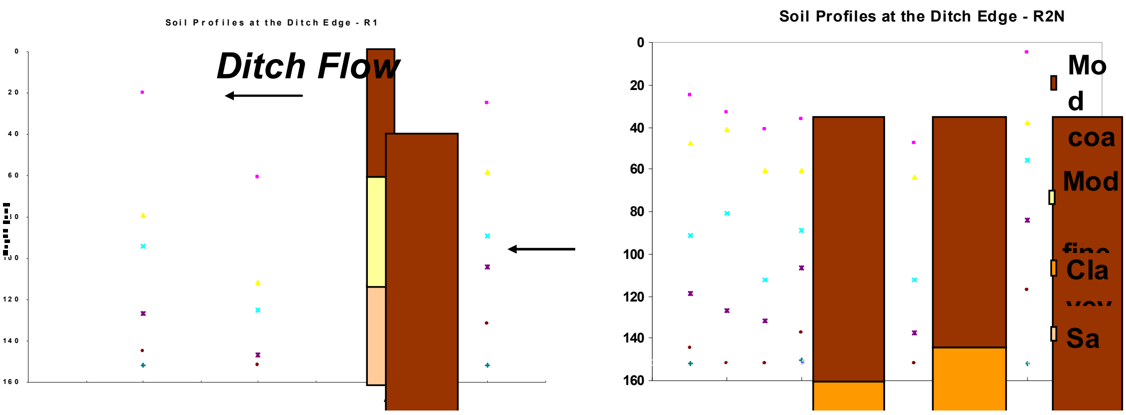

Figure 1. Soil textures at the ditch edges on buffers without (R1) and with (R2N) control structures. Redox potentials suitable for denitrification were measured where subsurface soils were clayey.

Carbon

The carbon content of the soils R1 and R2 are discussed in the following section. Comparisons are made by location on the buffer, i.e., ditch edge versus the field edge. Note that the average percent carbon (averaged over all horizons from the soil surface to 152 cm) by location is nearly identical on R1 and R2N. At the ditch edge, average % C was 0.85 and 0.84 on R1 and R2N, respectively. At the 7.6 m field edge, average % C was 0.47 and 0.44, respectively, which is a decrease of slightly more than fifty percent. In addition, the 15.2 m buffer on R2N had an average % C content of 0.25, which again, is slightly more than a 50% decrease. Of more important value is the carbon content of soils deeper in the profile. The higher carbon content along the ditch edge is likely a result of vegetation growing along and in the ditch providing carbon deep in the profile. At the field edges, the amount of carbon available at the deeper depths is probably a result of the vegetation that has been or is present at the site and whether or not it is translocated deeper in the soil profile.

Conclusion

Understanding the relationship between factors that influence the effectiveness of practices, such as riparian buffers and controlled drainage, for improving water quality is crucial as requirements to meet water quality standards become law. Improper recommendations not only defeat water quality improvement, but also question the validity of the use of these best management practices. Important factors as to their effectiveness include soil texture, the availability of organic matter, and a geographically appropriate pH range of 5.0-6.0. Soil texture has an important influence on soil redox potential. At the ditch edge on R2, the buffer with controlled drainage, all locations were in a similar landscape. However, soil texture in the middle part of the buffer at the ditch edge was different than the two ends of the buffer. Soils in the middle were sandy, while the ends had soil textures that were higher in clay content. At 152 cm, soil redox potential values were high in sandy-textured soils, indicating that reducing conditions were not favorable, while soil redox values in soils with higher clay content were low. Redox potential values, as well as the absence of nitrate-nitrogen in water samples located from these locations and decreasing nitrate/chloride ratios (these data not shown), indicated that denitrification was most likely the pathway of loss. Also, following periods of rainfall, clayey soils behaved as temporary restrictive layers that impeded water flow, permitted reducing conditions to temporarily occur. Sandy soils did not exhibit this behavior. Carbon was located throughout all soil profiles, though it was generally accumulated in the surface horizons. Mean carbon content was highest along the ditch on both buffers and its location within the soil profile was not limited in abundance to the surface horizons. At the 7.6-m field edge, mean carbon content decreased by approximately 50%. At the 15.2-m field edge, mean carbon content decreased another 50%. Curiously, the mean carbon content on the ditch edge on R2N, exhibited a pattern that most likely is related to soil texture. Vegetation along the entire length of the ditch was fairly similar and uniform in abundance. In the sandy soils located at the middle of the buffer, the mean carbon content was much lower as compared to the higher carbon content of the clay soils.

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