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Conservation Effects Assessment Project (CEAP)
CEAP-Wetlands Science Note

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Role of Prior Converted Croplands on Nitrate Processing in Mid-Atlantic Agricultural Landscapes

Summary of Findings

This study was conducted to determine whether Prior Converted Croplands (PCCs) can substantially reduce nitrate (NO_3) export from watersheds and to describe new methods to map, identify, and model important areas in watersheds.

Nutrient and pollutant concentrations (including NO_3) were monitored at the outlet of two sub watersheds (Greensboro and Tuckahoe) of the Choptank River Basin, on the Delmarva Peninsula. Cropland area in the two watersheds is nearly identical, but the NO_3 discharge/loading in the Tuckahoe watershed is more than twice that in Greensboro.

The Greensboro watershed has a much higher percentage of poorly drained (hydric) soils. Hydric soils are often anaerobic because they are saturated and often have higher potentials for denitrification, and thus lower NO_3 concentrations if they have the same nitrogen inputs. Both watersheds contain drainage ditches through which excess nutrients are transported to groundwater, and "legacy" nitrate has accumulated in the groundwater system of each watershed.

In this CEAP Science Note, various techniques are used to show that the Tuckahoe watershed's limited ability to denitrify excess NO_3 is causing a buildup of NO_3 in the groundwater system over the years, contributing to NO_3 loading via base flow at the outlet of Tuckahoe watershed. We also show that the PCCs are substantially reducing nitrate export from the Greensboro watershed through denitrification occurring in hydric soils.

LIDAR and a modified Soil and Water Assessment Tool (SWAT) were used to predict denitrification potential in the soils of PCCs and to calculate mass of NO_3 lost to denitrification as a function of NO_3 concentration in soil, soil organic carbon content, and a basin-wide denitrification rate, adjusted for local temperature effects.

Results demonstrate that 1) PCCs play an important role in determining the fate of agricultural N in watersheds, 2) topographic metrics drawn from LiDAR-based denitrification potential can potentially be used to map and characterize the biogeochemistry of PCCs, and 3) models such as SWAT can be modified to better represent PCC influence at the watershed scale.

The overall message of this Science Note is that special emphasis should be placed on mapping, identifying and understanding hydrology and biogeochemistry of PCCs, not only because of their aforementioned role in alleviating nutrient export to streams and open waters, but also because of the potential of PCCs restoration to more functional wetlands in the future.

Background

Prior Converted Croplands (PCCs) are historic wetlands that were transformed (drained, dredged, filled or leveled) to support production of agricultural crops prior to "Swampbuster" provisions of the 1985 Food Security Act. Our research suggests that PCCs can substantially reduce nitrate export from agricultural watersheds in the region, an ecosystem function shared with natural and restored wetlands. The main objectives of this study are (1) to test the hypothesis that PCCs can substantially reduce nitrate export from agricultural watersheds and (2) to describe new methods to map, identify, and model these important areas. The wetland ecological service of "nutrient attenuation" helps reduce natural resources concerns associated with degradation of water quality in agricultural landscapes.

Watershed Scale Observations – Choptank River Basin

The Choptank River Basin has been designated as a study area for multiple Federal studies, including the USDA Conservation Effects Assessment Project (CEAP) and the USDA Long-term Agroecosystem Research (LTAR) Network (McCarty et al. 2014, McCarty et al. 2008). During these projects, USDA scientists have been continuously monitoring nutrient and pollutant concentrations (including NO_3) at the outlet of two subwatersheds (Greensboro and Tuckahoe) of the Choptank River Basin, on the Delmarva Peninsula (Figure 1). The Greensboro watershed is slightly larger than the Tuckahoe watershed (290 vs 221 km^2) and has a smaller percentage of cropland cover

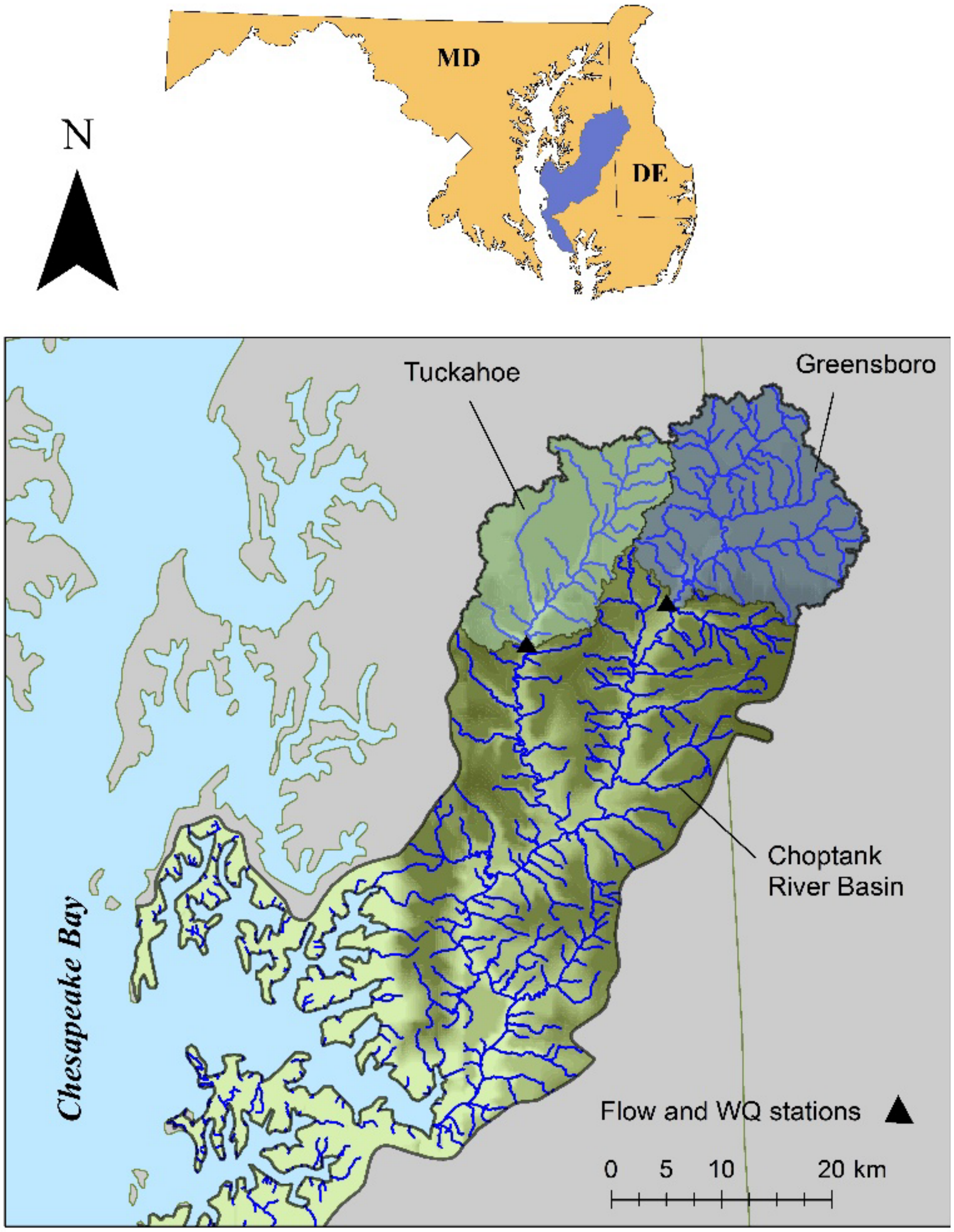

Figure 1. Locations of Greensboro and Tuckahoe watersheds within the Choptank River Basin on the Delmarva Peninsula in the Mid-Atlantic region of North America. Locations of USGS flow and USDA water quality stations are shown on the map.

(36.1 % vs. 54.0 %). However, the total area of cropland in the two watersheds is comparable (104 km^2 in Greensboro, 119 km^2 in Tuckahoe). Knowing that agriculture is the main source of nutrient discharge in the Choptank River Basin (Ator and Denver 2015), one would predict that the two watersheds would discharge comparable amounts of NO_3 at their outlets; however, this was not observed. As shown in Figure 2, NO_3 loading in the Tuckahoe watershed is more than twice that in Greensboro. This is most likely due to differences in watershed soil properties, indicated by the distribution of hydric soils within the two watersheds. A detailed look at soils of the Greensboro and Tuckahoe watersheds (Table 1) reveals that the Greensboro watershed has a substantially higher percentage of poorly drained soils compared to Tuckahoe (62% vs. 43%). Subwatershed data on agricultural management and conservation practices are not available, but comparable cropland areas and drainage water management practices via surface ditches support the observed effect of differing hydric soils areas on reported NO_3 concentrations

More importantly, roughly 49% of croplands in Greensboro have poorly drained soils as compared to 32% of croplands in Tuckahoe. Much of these croplands with poorly drained soils require drainage ditches to extract excessive soil water and make conditions favorable for crop production. Within both watersheds, ground water has a greater nitrate loading effect than surface water. Even though the Tuckahoe and Greensboro have surface drainage ditches (more in Tuckahoe than Greensboro), excess nutrients can be transported to the groundwater.

Over the years, "legacy" nitrate has accumulated in the ground water and is consistently delivered to streams through base flow. Base flow constitutes a large portion of total flow in the stream; therefore, much of the "legacy" nitrate in ground water is transported to the streams in both watersheds. However, the background concentration of nitrate in Greensboro's ground water tends to be smaller than in Tuckahoe's, because a greater portion of the applied nitrate is denitrified in the hydric soils of Greensboro. The nitrate delivery mechanism in both watersheds is comparable; however, the Greensboro watershed has a lower ground water nitrate concentration, resulting in less nitrate delivery via base flow to the stream.

In this CEAP Science Note, we test the hypotheses that (1) the Tuckahoe watershed's limited ability to denitrify excess NO_3 is causing a buildup of NO_3 in the groundwater system over the years, contributing to NO_3 loading via base flow at the outlet of the Tuckahoe watershed, and (2) the PCCs are substantially reducing nitrate export from the Greensboro watershed through denitrification associated with hydric soils.

Evidence From Scientific Literature

Poorly drained soils of PCCs often exhibit anaerobic conditions because they are saturated. Compared to well drained soils, which typically remain aerobic, poorly drained soils have higher potentials for denitrification, and thus lower NO_3 concentrations assuming the same nitrogen inputs (Denver et al. 2014, Hively et al. 2011, McCarty et al. 2014, Ator and Denver 2015). On the Delmarva Peninsula, the saturated conditions that promote denitrification are common in current and historical wetlands (Denver et al.

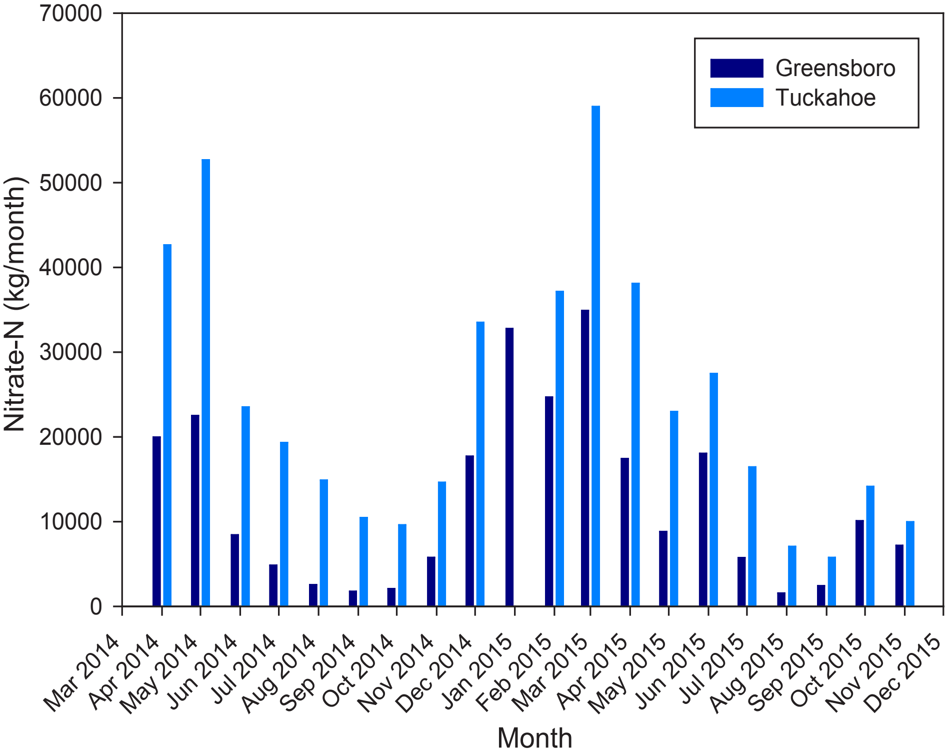

Figure 2. Bar plots of monthly NO_3 loadings from Greensboro and Tuckahoe watersheds. Data collection was performed by USDA.

2014, Duff et al. 2008, Pucket et al. 2008, Jordan et al. 2007) and along groundwater flow paths in organic-rich sediments (Böhlke and Denver 1995, Denver et al. 2010). The last category is particularly important in the Choptank Basin, where many wetlands have been ditched and drained for agriculture (Norton and Fisher 2000). Often, because of the intrinsic properties of poorly drained soils (such as texture), even when these soils are "drained," the drainage is at best only partially effective in lowering the water table in these soils and is less effective some distance away from the drainage structure. Figure 3 shows this effect on crop growth through a wet and a dry year on a number of ditched PCCs in the study watershed. In the wet year, crops of PCCs suffer from excessive moisture levels in the soil; and crops surrounding ditches suffer the most. For a given dry year, crops generally do better in PCCs, as crops use the residual moisture in the soil. The areas surrounding ditches tend to have more soil moisture and thus healthier crops in dry years.

The potential for denitrification in poorly drained, hydric soils of PCCs is likely higher than drained soils because the hydric soils have a greater chance of being anoxic/anaerobic as a result of slow infiltration capacity and/or shallow water table depths. Koskelo (2008) demonstrated that base flow NO_3 concentrations on the Delmarva Peninsula decreased with increasing area of hydric soils within forests, likely due to greater denitrification in these areas. Similar findings were reported by Norton and Fisher (2000) who found that forests with hydric soils showed a strong negative correlation with stream total nitrogen (TN) and NO_3 in the Choptank Basin. Denver et al. (2014) collected hydrologic, geochemical, and water quality data from a set of PCCs for roughly 2 years (2007-2008) and observed that when the zone of reducing conditions associated with the wetland extended through the entire thickness of the surficial aquifer, the wetland was effective at reducing the overall flux of nitrate that passed through the wetland sediment. In studies by Hively et al. (2011) and McCarty et al. (2014), monthly base flow stream samples from 15 agricultural sub-watersheds of the Choptank River (2005 to 2007) were analyzed for mean nitrate concentrations. Nitrate concentrations were greater ($p=0.0001$) in the well-drained, upland hydrogeomorphic region than in poorly drained upland, reflecting increased denitrification and reduced agricultural land use intensity in the poorly drained landscape, due to the prevalence of hydric soils. Furthermore, nitrate was inversely correlated to percent hydric soils of each sub-watershed ($p< 0.001$), and a moderate (but significant) inverse relationship was observed between nitrate and cropland on hydric soil ($p<0.01$).

Based on these data, the authors concluded that 1) smaller nitrate concentrations from poorly drained subwatersheds were most likely due to greater nitrate reduction within the subwatershed, as opposed to less cropland and therefore less nitrate-N application and 2) a metric for measuring the amount of cropland on hydric soils appears to be a more sensitive indicator of the biogeochemical potential for denitrification of agricultural N (than more simply the percent land area with hydric soils within a watershed), because of the strong root zone and vadose zone interactions as nitrate-N moves into groundwater under the croplands.

Use of LiDAR To Predict Denitrification Potential in PCCs

A novel method has been developed by USDA scientists to predict denitrification potential (assessed by denitrification enzyme activity or DEA) in the soils of PCCs. This method includes use of topographic metrics (topographic relief, topographic wetness index,

Table 1. Percentage of different soil drainage classes within the Greensboro and Tuckahoe watersheds.

Soil drainage class	% Greensboro	% Tuckahoe
Excessively well drained	3.0 (1.8)*	0.2 (0.0)
Well drained	17.7 (28.9)	36.2 (48.4)
Moderately well drained	16.8 (20.8)	20.6 (19.4)
Somewhat poorly drained	3.0 (3.8)	0.5 (0.3)
Poorly drained	34.2 (29.3)	31.5 (25.4)
Very poorly drained	25.3 (15.4)	11.0 (6.5)

*Values in parentheses denote percent of that soil type covering agricultural land.

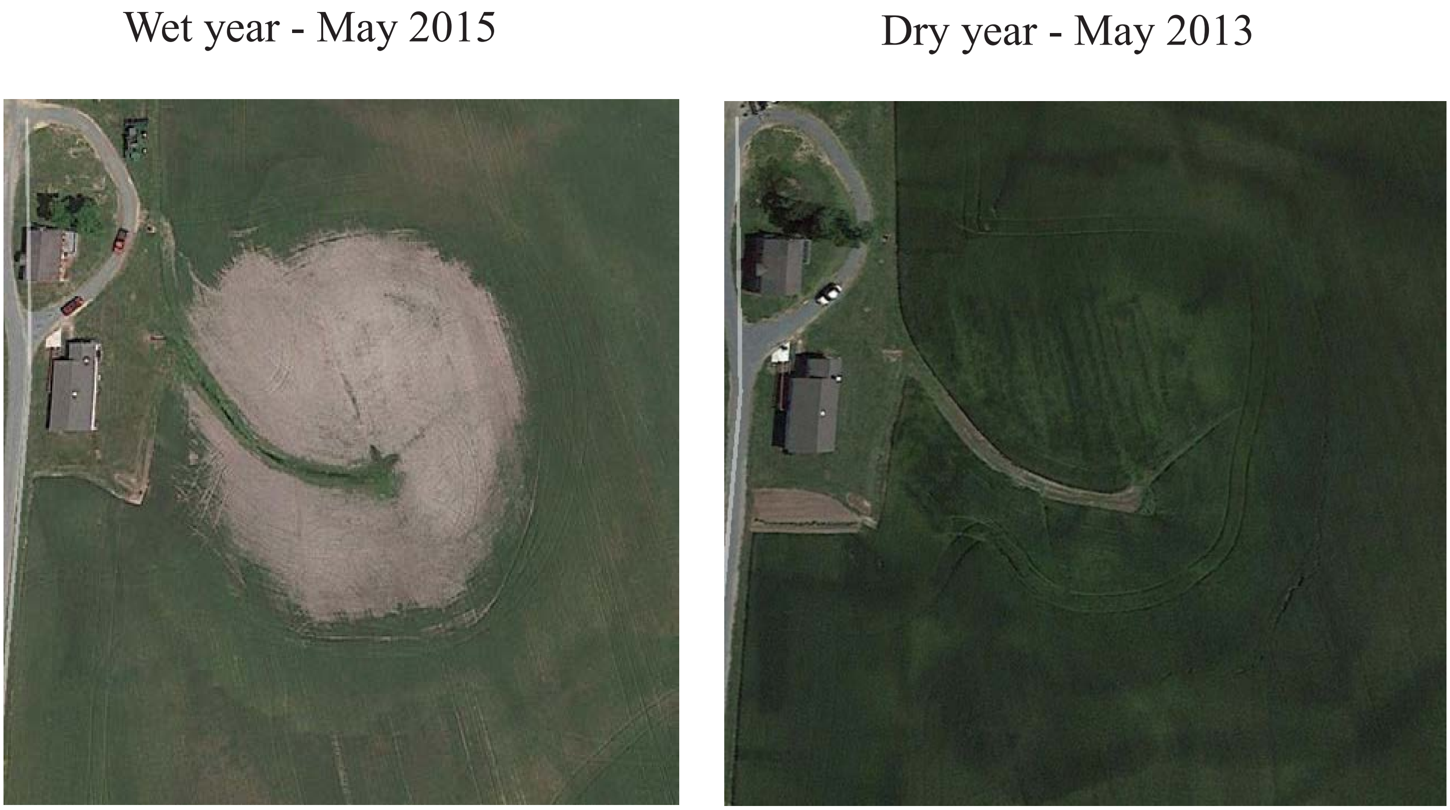

Figure 3. Aerial view showing crop growth patterns in May at PCCs for wet (left) and dry (right) years. Low biomass exists in the wet year and high biomass occurs during the dry year.

and topographic openness) derived from LiDAR-based high-resolution DEMs (Digital Elevation Models) as predictors for DEA activity along the topographic gradient of PCCs (Figure 4). The topographic openness index is a metric that measures the viewshed (e.g., the amount of observable sky) of a point on a landscape surface. Positive openness generally shows high values at convex locations on a surface such as ridges with low positive values indicating concave areas such as depressions (Yokoyama et al. 2002). Topographic relief is a widely used non-local topographic index, and has been found to help characterize denitrification patterns by depicting the distribution of soil organic matter and soil water content (Lang et al. 2013). The topographic wetness index (TWI), as a combined topographic metric, considers both slope and upslope contributing area associated with runoff generation, and thus has been used to characterize soil wetness.

In a study performed on three PCCs in the headwater region of the Choptank River Watershed, denitrification enzyme activity (DEA) was measured on multiple samples, extracted along the elevation gradient of each PCC. A preliminary regression model built using the three topographic metrics explained 53% of the variation in denitrification potential for the study PCCs ($R^2 = 0.53$):

$$Log\ (DEA) = 0.672 + 0.316 \times Relief + 0.14 \times TWI - 1.1 \times Openness$$

Relief explained the greatest amount of variability for DEA ($R^2 = 0.51$), followed by TWI ($R^2 = 0.44$) and openness ($R^2 = 0.43$). The model shows that high DEA is strongly correlated with depressions in croplands (i.e., prior converted croplands).

Modeling PCCs at the Watershed Scale

The Soil and Water Assessment Tool (SWAT) is a semi-distributed, process-based, long-term hydrologic and water quality model developed by U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS). SWAT was developed for assessing long-term impacts of management practices and non-point source pollutions in complex watersheds and is a widely recognized tool for evaluating effectiveness of BMPs (best management practices)(Arnold et al. 2012).

In the current standard model, SWAT calculated the mass of NO_3 lost to denitrification as a function of NO_3 concentration in soil, soil organic carbon content, and a global (basin wide) denitrification rate that is adjusted for local temperature effects. This method makes minimal distinction between different soil types when estimating mass losses for denitrification, as it lacks the capacity to account for higher denitrification losses in soils that exhibit more favorable conditions for anaerobic microbial activities, such as hydric soils in PCCs. To address this problem, Sharifi et al. (2016) modified the SWAT model's source code to assign various denitrification rates to different soil groups, with higher rates assigned to soils with higher denitrification potential. SSURGO, a nationally available soils database was used to identify soils with higher denitrification potential. SSURGO divides soils into six classes accord-

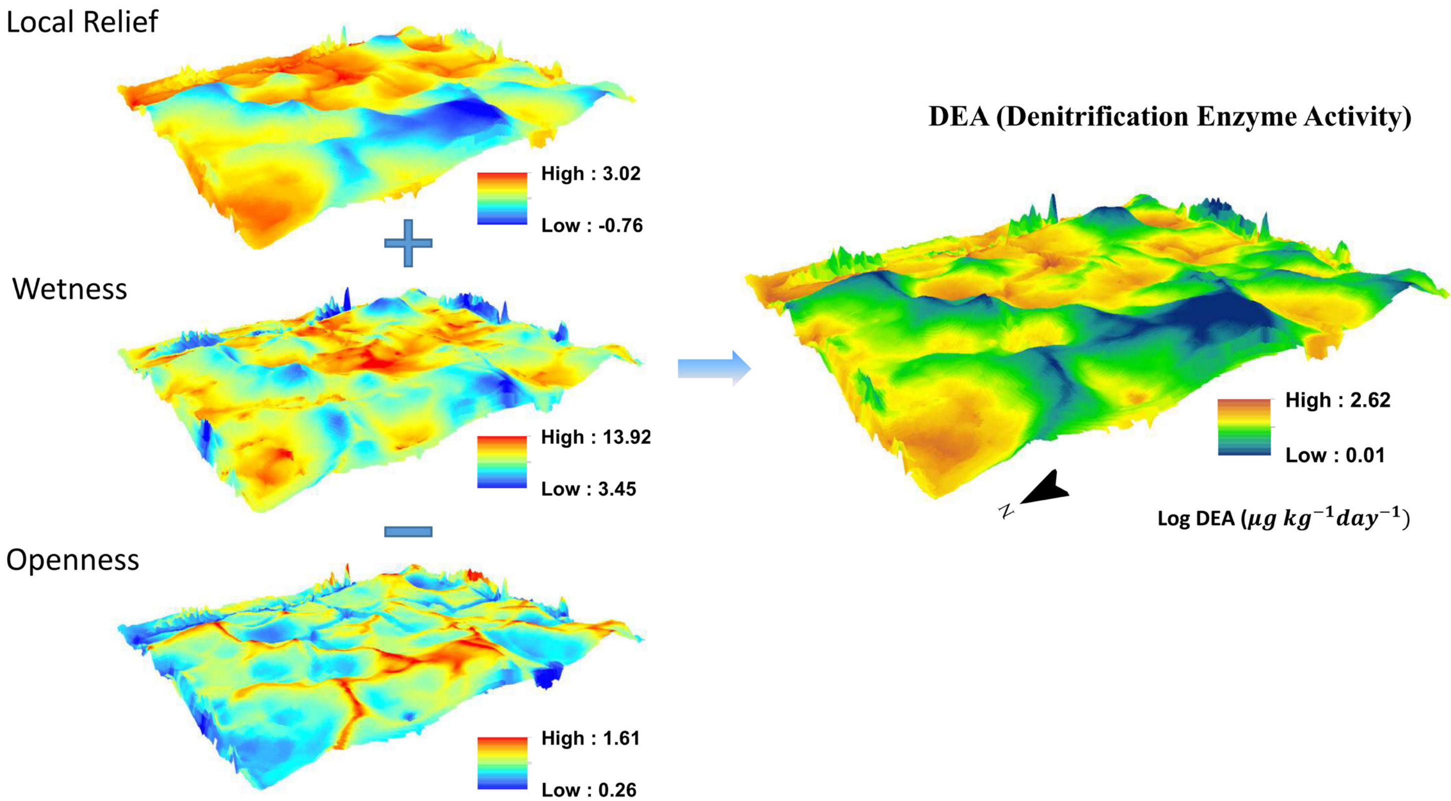

Figure 4. DEA (denitrification enzyme activity) can be predicted using topographic metrics extracted from high-resolution LiDAR maps shown above..

ing to drainage characteristics (very poorly drained, poorly drained, somewhat poorly drained, moderately well drained, well drained, and excessively well drained). Consequently, well drained soils were assigned lower denitrification ranges and poorly drained soils were allocated higher ranges for denitrification rate in the model.

When the modified model was applied to the Greensboro watershed, spatial representation of denitrification in the landscape was enhanced dramatically, and it was easy to clearly distinguish areas of high denitrification potential (hot spots or critical areas). Figure 5 shows an aerial image and a soil map of a typical cropland in the Greensboro watershed. As seen on the aerial photograph, the poorly drained soils in the field have reduced crop biomass. The bottom panels of Figure 5 show the spatial representation of denitrification loss rates estimated by the conventional and modified SWAT models.

This spatially explicit information can be used to not only improve the understanding of environmental processes and interactions with agronomic practices, but can also guide the implementation of conservation practices. For example, the function of these critical zones could be enhanced through the placement of controlled drainage structures to encourage soil saturation, and thus denitrification, as cropping schedules allow. In addition to water quality benefits, controlled drainage management can potentially improve crop yield beyond the typical crop response to traditional drainage, particularly in dry years. With proper management, the drainage outlet can be raised after planting to potentially store water for crops during dry years.

The novel approach described earlier (use of topographic metrics as predictors of biogeochemical activity) can also be used to disaggregate existing soil databases (such as SSURGO) into different biogeochemical zones. The resulted maps can then be used to add further refinement to landscape/watershed models.

Conclusions

Findings from the Mid-Atlantic Regional Conservation Effects Assessment Project (CEAP-Wetlands) have demonstrated that currently farmed historical wetlands (i.e., PCCs), are likely to have a considerable effect on water quality in the Mid-Atlantic Coastal Plain (Denver et al. 2014, McCarty et al. 2014, McCarty et al. 2008, Kluber et al. 2014, Ducey et al. 2015). The ability to enhance scientific understanding of these areas at the watershed scale is vital to improving water quality in the Chesapeake Bay. We have demonstrated that 1) PCCs play an important role in determining the fate of agricultural N in watersheds, 2) Topographic metrics drawn from LiDAR-based DEMs can potentially be used to map and characterize the biogeochemistry of PCCs, and 3) Models such as SWAT can be modified to better represent PCC influence at the watershed scale.

The overall message of this Science Note is that special emphasis should be placed on mapping, identifying, and understanding the hydrology/biogeochemistry of PCCs, not only because of their aforementioned role in alleviating nutrient export to streams and open waters, but also because of the potential that PCC restoration offers to more functional wetlands in the future.

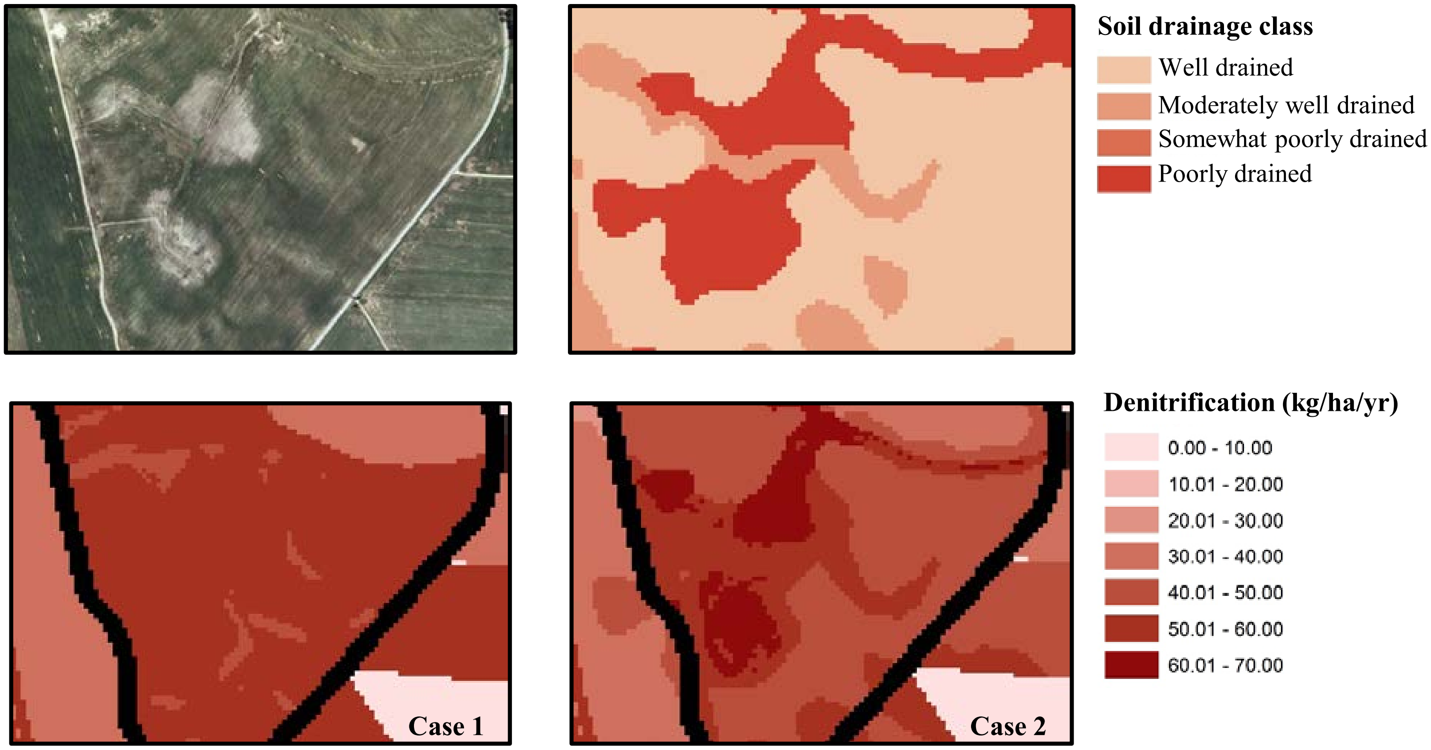

Figure 5. Aerial image (top left) and soil map (top right) of an agricultural plot in the Greensboro watershed. The bottom panels show the spatial representation of denitrification loss rates estimated by case 1 (left; control) and case 2 (right; distributed denitrification) models.

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