Surficial Oxygen Transfer into Treatment Lagoons and Potential N Pathways Resulting in Dinitrogen Gas Emission

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Abstract

Surficial oxygen transfer plays an important role when analyzing the complex biochemical and physical processes responsible for ammonia emission and removal in the animal waste treatment lagoons. This study 1) presents the synthesis of a new, unified equation for oxygen mass transfer coefficients based on the gas transfer data in the literature of the last 50 years and 2) discusses the potential nitrogen pathways responsible for the dinitrogen gas emissions observed from the treatment lagoons.

The new empirical oxygen-transfer equation is a function of Schmidt number and wind speed. With this new equation, the maximum surficial oxygen fluxes into the treatment lagoons were estimated. The stoichiometric amounts of the maximum dinitrogen gas production per kg O_2 were calculated based on the three different biological pathways for ammonia removal in the treatment lagoons; classical nitrification-denitrification, partial nitrification-denitrification, and partial nitrification-Anammox. Comparing the stoichiometric N_2 production with the observed N_2 emission data, the classical nitrification-denitrification pathway appears to be the dominant biochemical pathway for nitrogen removal. However, one N_2 emission data set with a much higher value than that can be supported by known biological processes also suggests that non-biological nitrogen process may also be important in these treatment lagoons.

Introduction

Anaerobic treatment lagoons are commonly used to treat wastewater, which is flushed from livestock operations (Bicudo et al., 1999; Hunt et al., 2003; NRCS, 1992; Poach et al., 2003). While specific lagoon characteristics vary with design, geographic location, time of year, and loading rates; conditions are generally favorable for some level of ammonia volatilization and denitrification. Ammonia volatilization has been thought to be substantially related the reduction of nitrogen, because the lagoons were perceived to be 1) highly suitable for ammonia volatilization and 2) limited in oxygen necessary for nitrification/denitrification. However, recent results have presented somewhat of an enigma for emissions from anaerobic lagoons – lower than expected ammonia and higher than expected dinitrogen gas emission rates from the treatment lagoons (Harper et al., 2000; Harper et al., 2004).

The high dinitrogen-emission rate data suggested the possibility that ammonia was oxidized to nitrate/nitrite by nitrifiers, the precursors for a subsequent denitrification step in production of dinitrogen gas. Because oxygen is an essential electron acceptor for the nitrification step, the demanding question is; where does the oxygen come from and how much oxygen in the air can be transported into a lagoon through its water surface exposed to the air. Wind can produce the necessary turbulence to promote the surficial oxygen transport process. The key question is whether the mass of the transferred oxygen could adequately support the nitrification step enough to produce dinitrogen gas to the extent of the observed magnitudes.

This study presents a new unified equation of oxygen transfer coefficient applicable to the anaerobic treatment lagoons based on extensive literature review, and discusses the potential nitrogen pathways responsible for the high dinitrogen gas emission.

Methodology

In developing the new unified oxygen transfer coefficient correlation, we first compiled the K vs.-wind speed observations of the water bodies where wind was the major turbulence-causing agent. We attempted to obtain raw data directly from published articles, and we were successful in most cases. However, a few authors reported their findings only in graphical forms. In those cases, we used the TatukGIS Viewer ™ (TatukGIS, Inc., Version 1.1.1.166) in order to estimate the values of data from the scanned images. These compiled data points include the transfer coefficients of the liquid-side controlled gases (O_2, SF_6, N_2O, CO_2, and ethylether) obtained from various laboratory wind-tunnels, floating reaeration devices in open water, and natural open waters. The transfer coefficients of these gases were normalized to O_2 and the wind speed to 10 m reference height (U_{10}) using the Schmidt number ratios and the seventh-root law (Ro and Hunt, 2006).

Results and Discussion

New Unified Oxygen Transfer Equation

A total of 297 transfer coefficient data were compiled from gas exchange studies conducted in laboratory wind tunnels of varying sizes and various field sites. If these data were fitted empirically with U_{10} only, as frequently done by previous researchers with their individual data; the effects of other important variables on transfer coefficients would not be revealed. Both molecular diffusivity of oxygen and wind-induced shear stress on water surface play an important role in the surficial oxygen transfer process, and they should be included in the new equation. We proposed the following mathematical form to fit the compiled data:

$$K_L = aSc^{-1/2}U_{10}^{b}\left(\frac{\rho_a}{\rho_w}\right)^{1/2} \qquad 1. \quad .$$

where a and b = arbitrary constants,
K_L = mass transfer coefficient (m/s),
Sc = Schmidt number (ν/D),
ν = kinematic viscosity of water (m^2/s),
D = molecular diffusivity of gas (m^2/s),
ρ_a = air density (kg/m^3),
ρ_w = water density (kg/m^3),
U_{10} = 10-m wind speed (m/s).

Equation 1 is similar to the formulation developed by Deacon (1977), which was based on the turbulent boundary-layer theory. The friction velocity of the Deacon's model is replaced with a power function of a more convenient wind-speed parameter, U_{10}. The two arbitrary constants of the non-linear equation were estimated using the MSExcel® Solver function. The resulting equation is:

$$K_L(cm/h) = 170.6 \cdot Sc^{-1/2}U_{10}^{1.81}\left(\frac{\rho_a}{\rho_w}\right)^{1/2} \qquad \text{for} \quad U_{10} < 0 \qquad 2.$$

The transfer coefficient (K_L) is in cm/h and the 10-m wind speed (U_{10}) is in m/s. The compiled transfer coefficient data fitted to the new equation quite well as evidenced by the coefficient of determination of 0.92 (Figure 1).

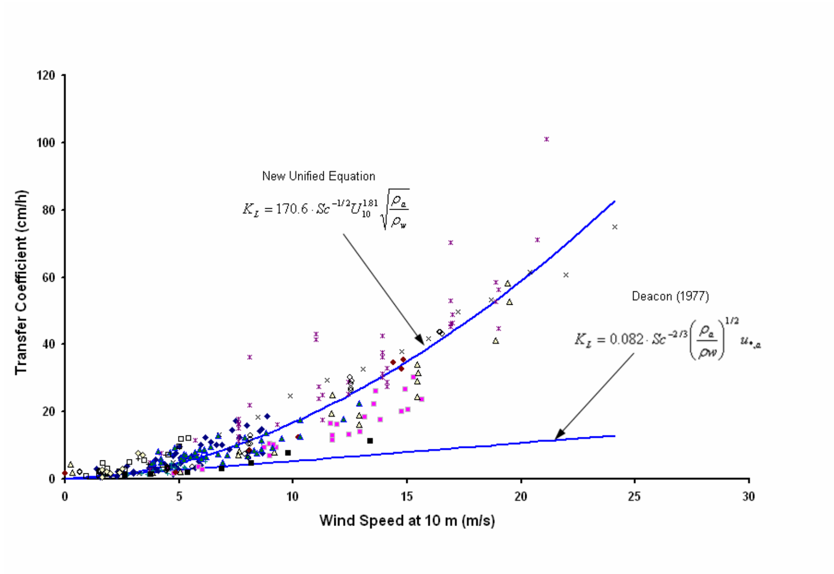

Figure 1. Predicting Compiled Transfer Coefficient with the New Equation and Deacon's Model

Implications on the Potential N Pathways in Treatment Lagoons

Using the new oxygen transfer coefficient equation, masses of oxygen transferred into treatment lagoons were estimated under relevant environmental conditions. Then, the maximum stoichiometric amounts of dinitrogen gas that could be produced per mass of oxygen transferred via three most probable biological N pathways were calculated. The maximum potential of producing dinitrogen gas per oxygen transferred via classical nitrification-denitrification, partial nitrification, and the complementary partial nitrification-Anammox pathways would be 0.24, 0.32, and 0.56 kg N_2 per kg-O_2, respectively (Ro et al., 2006). Assuming that all absorbed atmospheric oxygen was utilized for the ammonia oxidation processes, corresponding maximum N_2 production potentials from the three N pathways were plotted against U_{10} as shown in Figure 2.

There are only a few reports of N_2 gas emission observation from swine waste treatment lagoons (Harper et al., 2000 and 2004). We compared these N_2 emission data with the maximum N_2 production potential curves as shown in Figure 2. The average wind speed was converted to U_{10} using the seventh-root law. Most of the observed N_2 flux values were below the maximum N_2 production potential predicted from the classical nitrification-denitrification pathway, suggesting that these observed N_2 emission could be explained by the classical nitrification-denitrification pathway.

However, the large emission value of 85.6 kg-N_2 $ha^{-1}d^{-1}$ was far greater than the maximum N_2 production potential by the partial nitrification-Anammox pathway. Even for the least oxygen-demanding pathway of the partial nitrification-Anammox pathway, the rate of 85.6 kg-N_2 $ha^{-1}d^{-1}$ requires more than 6 m/s of prevailing wind speeds around the lagoons. We plotted the range of wind speeds (i.e., minimum to maximum) of the North Carolina FF farm to see if this range overlapped any of the maximum N_2 production potential lines; but the maximum N_2 production potentials of this range were still much smaller than the observed value of 85.6 kg-N_2 $ha^{-1}d^{-1}$. It seems that the alternative chemical denitrification or a yet-defined microbial consortium may indeed play an important role in these treatment lagoons as suggested by Haper et al. (2004) and Megonigal (2004).

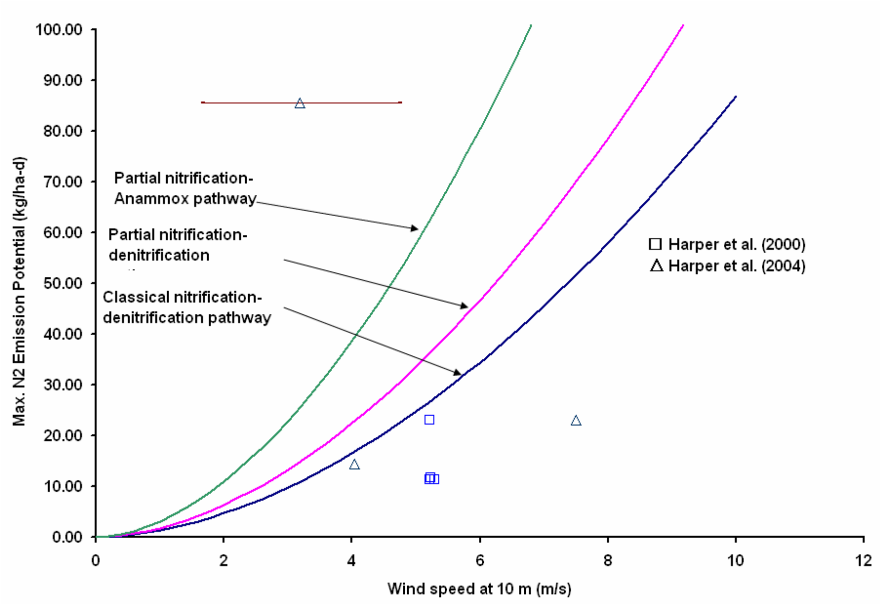

Figure 2. Comparing Existing N_2 Emission Data with the Max. N_2 Potential Curves

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