Wind-Driven Surficial Oxygen Transfer into Lagoons and Implications on Dinitrogen Emission

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Abstract

When analyzing the complex biochemical and physical processes responsible for ammonia and dinitrogen gas emission in the animal waste treatment lagoons, surficial oxygen transfer plays an important role. This research 1) reviews and analyzes research conducted during the last 5 decades on oxygen and other gas transfer into non-moving, open water bodies, 2) presents the synthesis of a new, unified equation for oxygen mass transfer coefficient, and 3) discusses the potential nitrogen pathways responsible for the dinitrogen gas emissions observed from the treatment lagoons based on the surficial oxygen transfer rate.

Both theoretically and empirically derived oxygen coefficients were evaluated using data derived from investigations in controlled wind tunnels, floating reaeration devices in open waters, and natural open waters. To facilitate the analysis, gas transfer coefficient correlations for other gases were normalized to oxygen, and wind speeds were normalized to 10-m height. Wind was the major turbulence agent facilitating the gas transfer processes. Generally, low wind speed did not significantly influence the transfer coefficients. However, the transfer coefficients increased, even exponentially, with higher wind speeds. Initial attempts to obtain reliable estimates of surficial oxygen transfer rates into treatment lagoons under relevant environmental conditions were not successful, primarily due to large variations among existing transfer coefficients. As a result, a new unified equation for predicting wind-driven gas transfer coefficients was synthesized. The new empirical 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 unit mass of O_2 transferred were calculated based on three most likely biochemical pathways for ammonia removal in the treatment lagoons. These were compared with observed dinitrogen gas emission data.

Introduction

Anaerobic lagoons are commonly used to partially treat the wastewater flushed from livestock operations (Bicudo et al., 1999; Hunt et al., 2003; NRCS, 1992; Poach et al., 2003). In these treatment lagoons, ammonia volatilization has been thought to be substantially related to the reduction of nitrogen from animal wastewater, 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. The nitrification process requires oxygen, which can be absorbed into the lagoon through the water surface exposed the air. This study 1) quantitatively estimates the mass of oxygen that can be transported into treatment lagoons via wind-driven turbulence and 2) investigates whether the mass of the transferred oxygen could adequately support the nitrification

step and to produce dinitrogen gas from the subsequent denitrification step to the extent of the observed magnitudes.

Methodology

We compiled the mass transfer coefficient K vs.-wind speed observations for water bodies from literature where wind was the major turbulence-causing agent. We obtained most raw data directly from the published articles; 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 et al., 2005a, b).

Results and Discussion
New Unified Oxygen Transfer Equation

Approximately 300 gas transfer data in the literature published over the last 50 years were compiled in order to develop a new unified oxygen transfer equation. These 300 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 and at field sites including ponds and lakes. Although quite scattered especially at higher wind speeds, Figure 1 shows us that there is definitely a positive relationship between the transfer coefficient and the wind speed.
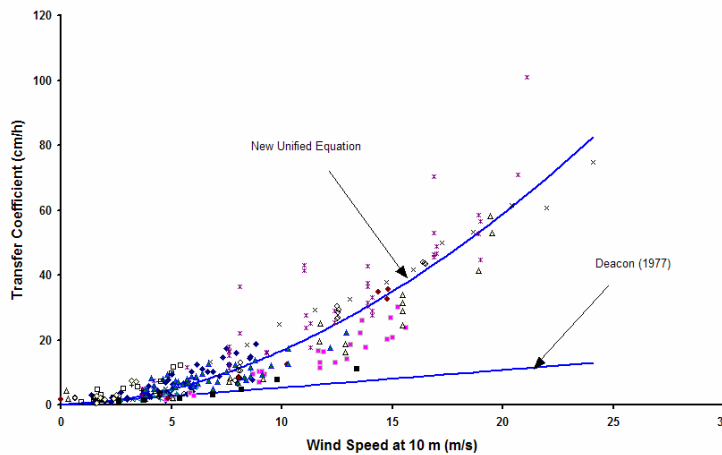

Figure 1. Compiled data fitted to the new unified equation

These data were fitted empirically to a mathematical form, which is similar to the formulation developed from turbulent boundary layer theory (Deacon, 1977).   The resulting equation is:

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

where K_L = mass transfer coefficient (cm/h),
    Sc = Schmidt number (v/D),
    v = kinematic viscosity of water (m²/s),
    D = molecular diffusivity of gas (m²/s),
    ρ_a = air density (kg/m³),
    ρ_w = water density (kg/m³),
    U_{10} = 10-m wind speed (m/s).

Deacon's equation reasonably well predicted the mass transfer coefficients at low wind conditions. However, for higher wind conditions, the water surface becomes rough with onset of ripple waves and the validity of Deacon's rigid-wall assumption quickly fades away.

Potential N Pathways in Treatment Lagoons

Although a comprehensive mathematical systems modeling of oxygen and nitrogen species in the anaerobic lagoons is very difficult at this time due to lack of kinetic information about the complex array of physicochemical and microbial reactions in the lagoons, we can still obtain valuable insights on the nitrogen pathways by performing simple stoichiometric analysis of the oxygen in the lagoons. Using Equation 1 at different temperatures, Figure 2 shows the values of the oxygen transfer coefficient at various temperatures.   Although the oxygen transfer coefficient increases with temperature, the solubility of oxygen decreases with temperature.   The maximum surficial oxygen mass transfer rates based on zero bulk DO concentration are plotted against the 10-m wind speed as shown in Figure 3.   The total oxygen mass transfer still increases with temperature, but the gap between the different temperatures decreases due to the decrease in oxygen solubility.
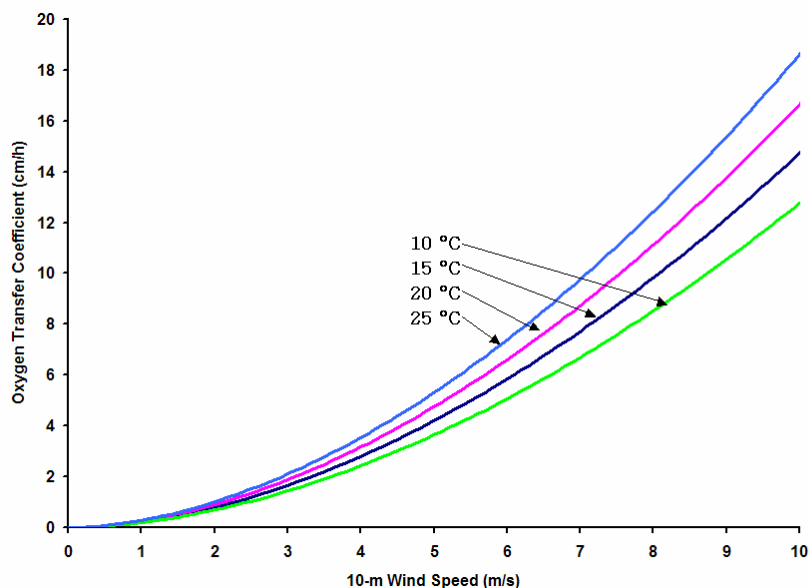

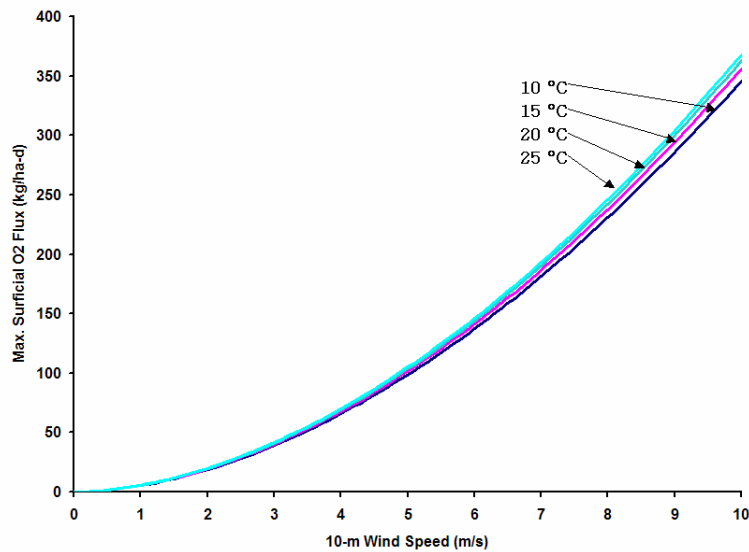**Figure 2 – K_L at different temperatures and wind speeds**

Figure 3 – Oxygen flux at different wind speeds

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., 2005b). 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 calculated.

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 to the calculated maximum N_2 production potential values. Most of the observed N_2 flux values were lower than the maximum N_2 production potential predicted from the classical nitrification-denitrification pathway, suggesting that the classical nitrification-denitrification pathway could explain the observed N_2 emission. However, one large emission value of 85.6 kg-N_2 $ha^{-1}d^{-1}$ was far greater than even the maximum N_2 production potential from the partial nitrification-Anammox pathway. It appears that an alternative chemical denitrification or a yet-defined microbial consortium may indeed play an important role in these treatment lagoons as suggested by Harper et al. (2004) and Megonigal (2004).

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