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Role of Wetland Plants as Oxygen and Water Pump into Benthic Sediments

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Wetland plants have evolved specialized adaptations to survive in the low-oxygen conditions associated with prolonged flooding. The development of internal gas space by means of aerenchyma is crucial for wetland plants to transport O_2 from the atmosphere into the roots and rhizome. The formation of tissue with high porosity depends on the species and environmental condition, which can control the depth of root penetration and the duration of root tolerance in the flooded sediments. The oxygen in the internal gas space of plants can be delivered from the atmosphere to the root and rhizome by both passive molecular diffusion and convective through-flow. The release of O_2 from the roots supplies oxygen demand for root respiration, microbial respiration, and chemical oxidation processes and stimulates aerobic decomposition of organic matter. Another essential mechanism of wetland plants is downward water movement across the root zone induced by water uptake. Natural and constructed wetlands sediments have low hydraulic conductivity due to the relatively fine particle sizes in the litter layer and, therefore, negligible water movement. Under such condition, the water uptake by wetland plants creates a water potential difference in the rhizosphere which acts as a driving force to draw water and dissolved solutes into the sediments. A large number of anatomical, morphological and physiological studies have been conducted to investigate the specialized adaptations of wetland plants that enable them to tolerate water saturated environment and to support their biochemical activities. Despite this, there is little knowledge regarding how the combined effects of wetland plants influence the biogeochemistry of wetland sediments. A further investigation of how the presence of plants and their growth cycle affects the biogeochemistry of sediments will be of particular importance to understand the role of wetland in the ecological environment.

Key words : wetland plants, oxygen, aerenchyma, diffusion, pressurized flow, evapotranspiration

INTRODUCTION

The essential characteristics to identify wetlands are: (1) hydric soils, (2) hydrophytic vegetation, and (3) wetland hydrology (Federal Interagency Committee for Wetland Delineation, 1989). When there is a lack of quantitative hydrologic data for delineation of wetlands determinations, an alternative indicator that can be readily observed during the field inspection should be utilized. The presence of an oxidized area, the rhizosphere, which is associated with living roots and the rhizome of hydrophytic vegetation, is the primary

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indicator to delineate wetlands (Mendelssohn *et al*., 1995).

Hydrophytic vegetations are plants which have adapted to growing in the low−oxygen conditions associated with prolonged saturation or flooding. To survive in anaerobic sediments of wetlands, wetland plants have evolved their specialized adaptations such as internal transport of gases and downward water movement due to evapotranspiration. The development of internal gas space is crucial for wetland plants to transport O_2 from the atmosphere into the roots and rhizome buried in the O_2 deficient sediments. The release of O_2 from the roots supplies oxygen demand for root respiration, microbial respiration, and chemical oxidation processes and stimulates aerobic decomposition of organic matter (Armstrong, 1979; Beckett *et al*., 1988; Reddy *et al*., 1989; Brix, 1993; Begg *et al*., 1994; Gibert and Frezel, 1998; Connell *et al*., 1999; Colmer, 2003). Another essential mechanism of wetland plants is downward water movement across the root zone due to water uptake (Brix and Schierup, 1989; Weisner *et al*., 1994; Martin and Reddy, 1997; Martin *et al*., 2003). Natural and constructed wetlands sediments have low hydraulic conductivity due to the relatively fine particle sizes in the litter layer and, therefore, negligible water movement (Mitsch and Gosselink, 1993; Fleming−Singer and Horne, 2002). This limits the infiltration of water and solute species into the sediments. Under such condition, the water uptake by wetland plants creates a water potential difference in the rhizosphere which acts as a driving force to draw water and dissolved solutes into the sediments.

The vegetative processes increase the flow of hydraulic mass flux toward the rhizosphere, create oxidized conditions in the otherwise anaerobic sediments, and enhance removal of nutrients (i.e. nitrate) (Winter and Kickuth, 1989a, b; Gilbert and Frenzel, 1998; Martin *et al*., 2003). Therefore, the root zone process (Kickuth, 1969−1984) driven by wetland plants plays an essential role to treat wastewater in the subsurface of constructed wetlands. Understanding the mechanisms through which wetland plants may influence the movement and distribution of dissolved solutes and the conditions of their reactions is necessary to manage and design constructed wetlands for wastewater treatment. This article reviews the existing information on oxygen release from roots followed by internal gas transport mechanisms and enhanced water movement into the sediments.

OXYGEN RELEASE INTO THE RHIZOSPHERE

Formation of aerenchyma

Saturated sediments of wetlands are generally characterized by the absence of oxygen and a reduced chemical condition. Since the diffusivity of oxygen in water is approximately 10,000 times slower than in air, the direct exchange between the atmosphere and submerged tissues is insignificant. Therefore, aquatic plants rooted in saturated sediments enhance the internal movement of oxygen via the aerenchyma (Armstrong, 1979). Aerenchyma is an airy tissue found in newly emerged adventitious roots (Trought and Drew, 1980), young seminal roots (Thomson *et al*., 1990), stems, and rhizomes (Sorrell and Orr, 1993), which contains of large air−filled spaces. The air−filled space of aerenchyma provides a low−resistance internal pathway for the exchange of gases between the plant parts above the water (i.e. shoot) and the submerged tissues (i.e. root) (Visser *et al*., 1997). The volume of air−filled space, porosity, can differ among plant species, even within a genus. Furthermore, porosity depends on the oxygen availability of root medium (Table 1).

Table 1. Porosity (% gas volume/tissue volume) in roots of wetland plant species grown in aerobic/anaerobic root medium.

Species	Porosity (%)		Reference
	Aerobic	Anaerobic	
Monocotyledonous species			
Typha domingensis	10−13	28−34	Kludze and DeLaune, 1996 Chabbi *et al*., 2000
Phragmites australis	43	52	Justin and Armstrong, 1987
Juncus effusus	31−40	36−45	Visser *et al*., 2000
Carex acuta	10	22	Visser *et al*., 2000
Dicotyledonous species			
Rumex palustris	15−30	32−45	Justin and Armstrong, 1987 Visser *et al*., 2000
Ranunculus flammula	9−11	30−37	Smironff and Crawford, 1983

Depending on the species and environmental conditions, the volume of air-filled spaces controls the depth of root penetration and the duration of root tolerance in the flooded sediments. For example, in the saturated sediments, roots of *Rumex thyrsiflorus* can penetrate deeper than those of *Rumex maritimus* due to the higher volume of air space (Laan *et al*., 1989).

Mechanisms of oxygen transport

Oxygen in the gas space of plants will be either consumed by cells in adjacent tissues or consumed in anaerobic sediments by radial diffusion into the rhizosphere at the root tips (Armstrong, 1979). The supply of oxygen which moves from the atmosphere to the root tip is affected by anatomical features of plants, such as: the extent of aerenchyma formation, diameter of the stele, arrangement of cortical cells, and a permeability barrier to radial oxygen loss (Armstrong and Beckett, 1987; Justin and Armstrong, 1987). Morphological characteristics such as root diameter and number of lateral roots and physiological processes such as respiratory demand for oxygen can control the longitudinal oxygen diffusion in roots (Armstrong, 1979; Colmer, 2003).

The dominant mechanisms to transport oxygen

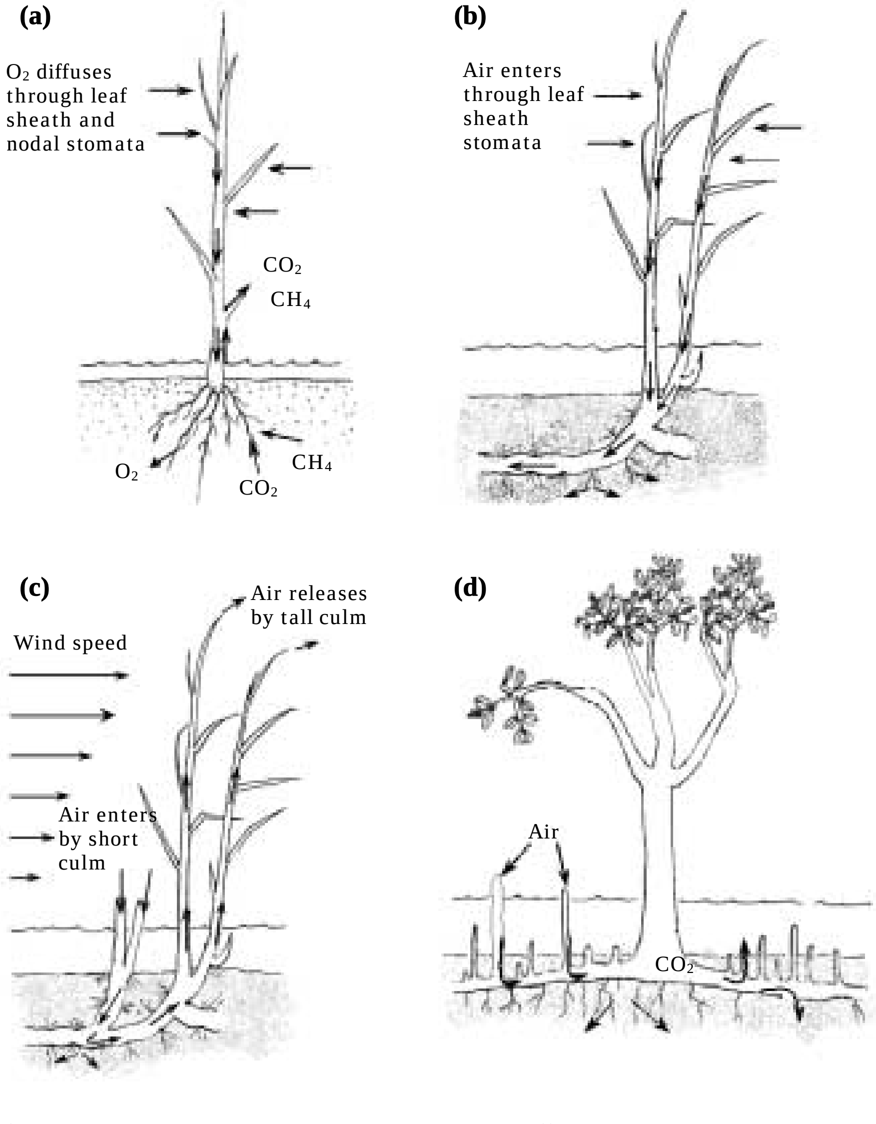

Fig. 1. Mechanisms of internal gases transport. (a) Passive molecular diffusion; (b) Convective through-flow; (c) Venturi-induced convection; (d) Gas exchange convection

in internal gas space system are passive molecular diffusion (Armstrong, 1979) and convective through-flow (Brix *et al.*, 1992 and 1996). Passive molecular diffusion is the random molecular movement from sites with higher concentrations to sites with lower concentrations. It was traditionally believed that the concentration difference gradients of the individual gases between aerial part of plant and rhizome and root drives internal transfer of gases in wetland plants (Fig. 1(a)). The rate of diffusion of a gas depends on the medium in which the diffusion occurs, the molecular weight of the gas, and the temperature. In the common reed, *Phragmites australis*, the O_2 concentration decreased from atmospheric levels (20.7%) in the aerial stems to low levels (3.6%) in the rhizomes, accompanied with a reverse-order gradient of CO_2 or CH_4 concentration (Brix, 1988). The concentration gradients of O_2 and CO_2 in the lacunae system showed that the internal diffusive transfer of O_2 plays a significant role in aeration of buried root systems.

Table 2. Measured convective through-flow rate of gases in wetland plants.

Species	Flow rate $\left[\frac{1}{\text{day}}\right]$	Reference
Nelumbo nucifera	12.0	Mevi-Schütz and Grosse (1988)
Hydrocleys nymphoides	0.34	Grosse *et al.* (1991)
Victoria amazonica	120	
Phragmites australis	23.04	Armstrong and Armstrong (1991)
Phragmites australis	0.6-1.2	Armstrong *et al.* (1992)
Eleocharis sphacelata R. Br.	1.44	Sorrell and Boon (1994)
Typha latifolia L.	5.0	Bendix *et al.* (1994)
Typha angustifolia L	11.5	

At the end of the last century, it was reported that a convective mechanism is involved in the flow of gases through internal gas-space of water lilies, floating-leaved plants, *Nuphar luteum* (Dacey, 1980 and 1981), and other wetland plants, *Phragmites australis* (Armstrong and Armstrong, 1990, 1991; Armstrong *et al.*, 1996). Convective through-flow of gases (Fig. 1(b)) is dependent on the generation of pressure gradient between two ends of a pathway within the plant body. The magnitude of pressure gradient and the resistance to gas flow controls the rate of convective through-flow. This enhances the oxygen concentration in the underground tissues and causes flushing of oxygen-depleted biogenic gases (i.e. CO_2, CH_4) from the rhizome to the atmosphere via dead and broken culms (Armstrong and Armstrong, 1990; Chanton and Dacey, 1991; Sorrell and Boon, 1994; Yavitt and Knapp, 1998). The convective through-flow of gases mainly depends on humidity induced diffusion of atmospheric gases across the stomata on living leaf sheaths and culm nodes in wetland plants (Knudsen diffusion) (Armstrong and Armstrong, 1990). Higher relative humidity within the plant, caused by constant evaporation from the cells adjoining the gasspaces, reduces O_2 concentration relative to those in the drier air outside of plants. This appears to be the major factor for diffusion gradients of atmospheric O_2 entry which pressurizes the internal gasspace. The significant resistance to Poiseuille flow, from leaf sheath to atmosphere through stomata, allows plants to pressurize gas flow as the atmospheric O_2 gases diffuse in. A gradient in total gas pressure in the internal gas space increases the O_2 partial pressure. This mechanism drives the convective through-flow of the gas mixture to the rhizome (Dacey, 1981; Armstrong *et al.*, 1992). Therefore, lower relative humidity outside of the plant will result in more rapid air diffusion into the plant and faster diffusion of water vapor outwards. This flow is maintained as long as the rate of water vapor outflow is equal to the rate of internal evapotranspiration. The rate of convective flow is related to atmospheric humidity, temperature, and light intensity. Table 2 shows wide range of convective through rate depending on the plant species and different environment condition. The convective flow is rapid under conditions of low atmospheric humidity and warm and sunny conditions (Armstrong and Armstrong, 1990 and 1991). When the environmental conditions are not favorable for inducement of convective flow, diffusion is the main process which delivers oxygen to the underground rhizome and root system. Since convective flow is much more effective than diffusion in supplying oxygen to the rhizome system, substantial diurnal and seasonal fluctuations have been observed in the aeration of rhizomes and the oxygen release from roots (Armstrong and Armstrong, 1990; Brix *et al.*, 1996).

Another type of pressurized gas flow is venturi-induced convection which, up to now, has been found only in *Phragmites australis* (Fig. 1(c)). The wind blowing across tall old culm has higher velocity which produces lower pressure due to venture effect. The pressure difference between tall old culm and short broken culm causes suction of air via culms which have been snapped off close to ground level, increases oxygen concentrations in the rhizome system, and ventilates oxygen-depleted biogenic gases (i.e. CO_2, CH_4) from the rhizome to the atmosphere via tall dead culms (Armstrong *et al*., 1992).

In addition, gas exchange between buried root tissue and surrounding water may induce convective gas flow in wetland plants (Fig. 1(d)). The black mangrove (*Avicennia nitida*) growing in the tidal zone has a number air roots (pneumatophores) with 20 cm to 30 cm, which stretches vertically out from buried horizontal root system (Scholander *et al*., 1955; Brix, 1993). The air roots with numerous lenticels (openings to the atmosphere) draw atmospheric O_2 into the root system when they are exposed to open air. As the rising tide covers the lenticels of air roots, respiratory O_2 demand of root decreases the gas pressure in the roots system. The produced CO_2 can dissolve in the pore water because CO_2 has 30 times larger solubility in water than O_2. The decreased gas pressure in root system again draws O_2 from the atmosphere by the falling tide.

Oxygen release from roots

Constructed wetlands planted with common reed, *Phragmites australis*, have been used to treat wastewater which flows laterally through the soil medium. The wastewater is purified during contact with the surfaces of the soil particles and roots and rhizomes of the reeds. The Root Zone Process, developed in the early 1970s in Germany (Kickuth, 1977), explains how the wastewater can be purified in wetland sediments. The sediments of wetlands are continuously water-saturated and therefore generally anaerobic. The ability of reeds to bring oxygen from the air via aerenchyma into the roots, moreover, and the rhizosphere of water saturated sediments supports aerobic microorganisms adjacent to the roots and rhizomes. This enables effective oxidative reactions to take place other than reductive reactions found in the saturated sediments. Plant physiologists have studied both the magnitude of oxygen diffusion in the rhizosphere and the effect of this diffusion on the redox potential of the sediments for over 40 years (Armstrong, 1967; Brix, 1990; Brix and Schierup, 1990; Armstrong *et al*., 1992; Brix *et al*., 1996). However, there is still considerable debate on the oxidizing potential of plant roots. These aeration processes have been evaluated directly by measuring radial oxygen flux from adventitious and lateral roots of *Phragmites australis* in oxygen depleted solutions, using cylindrical platinum electrodes surrounding the roots space (Armstrong, 1964, 1967 and 1994). In addition, aeration has been evaluated by measuring the change in the gas composition of the influx and efflux in the internal gas space of wetland plants (Brix and Schierup, 1990; Armstrong and Armstrong, 1991; Sorrell and Boon, 1994; Brix *et al*., 1996).

The radial oxygen loss, denoted as ROL [g O_2 cm^{-2} min^{-1}], is the rate of oxygen release from the roots, when the roots of plants are placed in saturated sediments. The flux of ROL depends on the concentration gradient of oxygen between aerenchyma and sediments and the resistance to radial oxygen diffusion. The flux of oxygen from the aerenchyma to the sediments aerates the rhizosphere of aquatic plants, changes both nutrient availability and microbial population, and prevents damage from soluble phytotoxins (i.e. Fe^{2+}) (Armstrong, 1971; Mendelssohn and Postek, 1982; Wang and Peverly, 1999).

Several methods have been applied to evaluate the flux of oxygen from the roots. Studies using analysis of oxidized material coating roots such as Fe plague (Mendelssohn and Postek, 1982) and application of indicator dyes such as methylene blue (Armstrong and Armstrong, 1988) provided qualitative information on the presence of oxidized area in the rhizosphere. Measurements of increased redox conditions in the rooted sediments provided quantitative evidence for oxygen release from the roots (Carpenter *et al*., 1983). Moreover, ROL can be measured directly by the cylindrical Pt electrode method of polarographic analysis (Armstrong, 1964, 1967, and 1994). Roots are passed into a cylindrical Pt electrode. The electrode/root configuration has a shell of liquid between the roots and inner the electrode surface. The amount of oxygen reduced by applied polarizing voltage to the electrode can be measured at the electrode surface as an electrical current in microamperes [μA]. The electrode therefore acts as an oxygen sink, a substitute for the oxygen sink in the soil. The amount of oxygen reduced by the electrode can be converted to the oxygen flux from the roots using the equation of Fick's Law (Armstrong, 1971):

$$f_{x=0,t} = \frac{I_t}{nFA} \quad (1)$$

where,

I_t : μA measured at root apex −μA residual = diffusion current in μA at time t after closing the electrode circuit

n : number of electrons required for the reduction of one molecule of oxygen, assumed to be 4

F : Faraday constant (96,500 coulombs)

A : surface area of the root within the electrode (cm^2)

$f_{x=0,t}$: oxygen diffusion flux at x = 0 cm from the platinum surface at time t (mole O_2 s^{-1})

Recently, O_2 microelectrode provided a detailed record of oxygen distribution with even higher spatial and temporal resolution (Armstrong *et al.*, 2000).

ROL was measured along the surface of roots from the root/shoot junction to the root tips to determine the change of ROL depending on the distance from the root tip. ROL fell rapidly from the root tip to the basal region. At 4−5 cm from the root tip, ROL approached zero due to a decrease in root wall permeability. Connell *et al.* (1999) observed a significant gradient of ROL from an average maximum value of 72 ng O_2 cm^{-2} min^{-1} at 0.5 cm from the root tip to 4 ng O_2 cm^{-2} min^{-1} at 3 cm from the root tip. Opposed to the trend of ROL along the root surface, the O_2 concentrations within the cortex of the roots progressively increased to the closer location of root/shoot junction (Jackson and Armstrong, 1999; Armstrong *et al.*, 2000; Visser *et al.*, 2000; McDonald *et al.*, 2002). The significant gradient of ROL despite of O_2 concentration in the cortex indicated a strong barrier to ROL in the root basal regions. The strong barrier to ROL along most of the root length reduced oxygen loss from the aerenchyma to the saturated sediments and enhanced longitudinal oxygen diffusion toward the root tips. This mechanism allows the roots of aquatic plants to penetrate into the saturated sediments and to grow in such an environment. Consequently, rhizosphere oxygenation is confined to the apical regions of roots (McDonald *et al.*, 2002). The rate of oxygen transfer into wetland sediments can be substantial and highly variable depending on the type of vegetation, root size, and oxygen demand of the sediments. In addition, oxygen release from the roots varies with the photosynthesis cycle of plants and wind speed over the surface. Table 3 summarizes the results of a number of measurements of aeration processes.

Table 3. Summary of oxygen flux rates into the sediments.

Plant name	Oxygen flux rate $\left[\frac{gO_2}{m^2\ \ day}\right]$	Reference
Typha domingensis Pers.	0.52−0.72	Dunbabin *et al.* (1988)
Phragmites australis	0.02	Brix (1990)
Phragmites australis	1.6−3.1	Gries *et al.* (1990)
Phragmites australis	5−12	Armstrong *et al.* (1990)
Phragmites australis	25	Armstrong and Armstrong (1990)
Phragmites australis	0.02	Brix and Schierup (1990)
Phragmites australis	8.1−21.6	Brix *et al.* (1996)

ENHANCED WATER MOVEMENT

Mechanisms of evapotranspiration

The plant roots act as an anchor in the sediments. They provide a place for the storage of carbohydrates and other organic molecules, and they serve as a site of synthesis for important molecules such as alkaloids and some hormones. Roots absorb and transport water and minerals upwards to the stem. To support biochemical activities, plants should replenish water lost by transpiration through the absorption of an equivalent amount of water from the sediment through the root system. According to a large number of anatomical and physiological studies, the region of most active water uptake occurs is near the root tip. Specifically, root hairs, the thin−walled outgrowths of epidermal cells on the root, are the regions of most rapid water uptake. Root hairs increase the absorptive surface area of roots and extend the contact of the root into the sediment pore volume (Hopkins, 1995).

Wetlands lose water both by open water evaporation, which removes water from the surface and results in increased concentration of solutes in the water column, and by transpiration, which

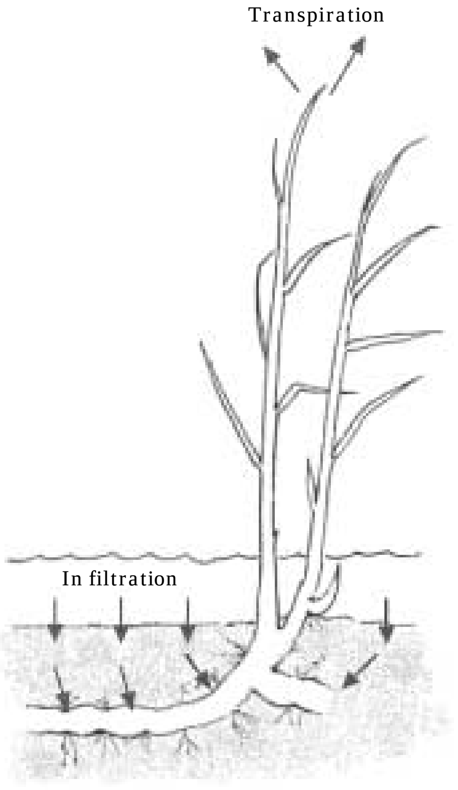

Fig. 2. Evapotranspiration induced water movement in wetland sediments.

removes water from the surface of plant leaves. Transpiration results in the flow of pore water movement in the sediments toward the rhizosphere to replace the water lost by plant uptake. Evaporation and transpiration are affected by incident solar energy, wind speed, and specific humidity gradient over the surface. Because of difficulties in measuring the effects of evaporation and transpiration separately, the combined concept of evapotranspiration has been used (Fig. 2). The concept of evapotranspiration is adequate in water budgets calculation, but not adequate in water transport calculation. While evaporation simply transports water vapor away from the open-water surface, transpiration results in the downward movement of sediment water toward the rhizosphere, in response to the water uptake by plants rooted in the sediments.

Measurements of evapotranspiration

There have been plenty of experiments and analyses to address whether a vegetation-covered water body has a larger or smaller evaporation rate compared to open-water surface. Investigations of water loss by aquatic plants, which have been conducted for nearly a century, have yielded a variety of contradictory results. Penfound and Earle (1948) observed that evapotranspiration rates for water surfaces covered by water hyacinth were up to three times greater than for an open-water surface. Benton *et al.* (1978) reported a water surface covered by vegetation evaporated water much faster than vegetation-free water surface. However, a number of studies point to a decrease in evaporation due to the presence of vegetation. Idso (1981) observed that the ratio of evaporation rate to open-water evaporation rate (E/E0) was less than one in large-scale wetland areas. Anderson and Idso (1987) found that two aquatic species, water hyacinth and water lily, decreased E/E0 ratio to less than one due to the minimum atmospheric turbulence and stomatal regulation. It appeared that the introduction of any type of vegetation on surface water does not increase the evaporation rate to a measurable degree. Subsequently, the measurement of water loss by surface water-level reading indicated that the relative rates of evaporation from vegetation-covered and open-water bodies is less than unity over extensive surfaces, and approach unity for vegetation that is young and vigorous (Kallin, 1999).

In spite of these debatable results, the importance of vegetation effects on water transport in the sediments still needs to be addressed. Aquatic plants can decrease evaporation from open-water surfaces. The presence of vegetation does not allow the transmission of solar energy onto the water surface, which results in the decrease in open-water evaporation. In addition, the vegetation reduces the humidity gradient between the water surface and the atmosphere by reducing the amount of wind across the water surface. Natural and constructed wetlands sediments have low hydraulic conductivity due to the relatively fine particle sizes in the litter layer (Mitsch and Gosselink, 1993; Fleming-Singer and Horne, 2002). This limits the infiltration of water and solute species into the sediments. Diffusive flux is recognized as a main mechanism that causes a net downward movement of water in the soil column. Under such condition, the presence of aquatic plants creates a water potential difference which acts as a driving force to draw water and dissolved solutes into the sediments. The removal of water from the leaves of plants causes the decrease of water potential around the rhizosphere, which induces infiltration of water including dissolved solute species from the overlying water column (Jaffe *et al.*, 2001; Xu and Jaffe, 2004). This process is similar to radial flow toward a pumping well. As a result, transpiration by plants can be recognized as a main process to control the water budget and transport of water in wetland sediments.

To estimate a long-term and regional evapotranspiration based on weather data, the Penman-Monteith Evapotranspiration equation is widely used (Allen *et al.*, 1989; Allen *et al.*, 1992).

$$E_t = \frac{\Delta(R_n - G) + \rho c_p \dfrac{(e_a - e_d)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_c}{r_a}\right)} \qquad (2)$$

where,

E_t : evapotranspiration (W m^{-2})
R_n : net radiation (W m^{-2})
G : soil heat flux (W m^{-2})
ρ : air density (kg m^{-3})
c_p : specific heat of dry air (J kg^{-1} °C^{-1})
e_a : saturation vapor pressure of air at air temperature (kPa)
e_d : saturation vapor pressure of air at dewpoint (kPa)
Δ : the slope of the saturation vapor pressure curve (kPa °C^{-1})
γ : the psychrometric constant (kPa °C^{-1})
r_a : aerodynamic resistance to turbulent transfer of sensible heat and vapor from the plant surface into the atmosphere at the wind measurement height (s m^{-1})
r_c : bulk canopy resistance (s m^{-1})

The Penman-Monteith equation accounts for aerodynamic resistance to turbulent diffusion and stomatal resistance to vapor transport. Evapotranspiration rates for cattails, computed using the Penman-Monteith equation, was 4 to 14 mm day^{-1} (Allen *et al.*, 1992; Abtew *et al.*, 1995) which induced a vertical movement of water of 5.8 mm day^{-1} to 20.3 mm day^{-1} in the sediments with porosity equal to 0.55.

Gunderson (1989) observed that the average annual evapotranspiration (127 cm yr^{-1}) rate accounted for less than 85% of water loss from atmospheric inputs (140 cm yr^{-1}). Dominant aquatic plants (*Cladium jamaicense* and *Typha domingensis*) in the wetlands can influence evapotranspiration rates through transpiration and stomatal control over the range of ambient temperature, vapor pressure, and light intensity (Koch and Rawlik, 1993).

SUMMARY

As ecotones located between dry terrestrial upland and permanently flooded deepwater, wetlands are used to treat wastewater from natural and human sources. The most notable features of wetlands are water saturated sediments and vegetation adapted to survive in anoxic sediments (Mitsch and Gosselink, 1993). The formation of tissue with high porosity, aerenchyma, is crucial for wetland plants to transport atmospheric oxygen into water saturated anoxic sediments. The porosity of plant tissue depends on the species and environmental condition (aerobic/anaerobic), which can control the depth of root penetration and the duration of root tolerance in the flooded sediments (Smironff and Crawford, 1983; Justin and Armstrong, 1987; Kludze and DeLaune, 1996; Chabbi *et al.*, 2000; Visser *et al.*, 2000). The oxygen in the internal gas space of plants can be delivered from the atmosphere to the root and rhizome by both passive molecular diffusion (Armstrong, 1979) and convective through-flow (Brix *et al.*, 1992 and 1996). The transported oxygen is consumed in anaerobic sediments by radial diffusion into the rhizosphere. The supply of oxygen is affected by distinguished characteristics of wetland plants such as the extent of aerenchyma formation, arrangement of cortical cells, root diameter, and number of lateral roots as well as environmental conditions (Armstrong, 1979; Armstrong and Beckett, 1987; Justin and Armstrong, 1987; Colmer, 2003). In addition, evapotranspiration of plants results in the flow of pore water movement in the sediments toward the rhizosphere to replace the water lost by plant uptake. Because of the low hydraulic conductivity of wetland sediments, evapotranspiration is an essential driving force to draw both water and dissolved solutes into the sediments.

A large number of anatomical, morphological and physiological studies have been conducted to investigate the specialized adaptations of wetland plants that enable them to tolerate water saturated environment and to support their biochemical activities. Despite this, there is little knowledge regarding how the combined effects of wetland plants influence the biogeochemistry of wetland sediments (Kallin, 1999; Jaffe *et al.*, 2001; Choi, 2004). Oxygen leakage from the roots oxidizes rhizosphere and detoxifies harmful substances near the root and rhizome. Downward water movement driven by plant uptake may affect distribution of dissolved solutes and, thereafter, their reactions in the modified environment. By the virtue of functions of wetland plants, wetlands have been utilized to purify water flowing through rhizosphere of the sediments. The studies of plant physiology and effluent analysis have provided removal efficiencies of nutrients and metal ions, but much remains to be investigated regarding modified redox conditions and activities of microorganisms by the characteristic features of roots; for example, the change of redox condition and microbial metabolites depending on the distance from the roots, species of plants, environmental conditions (i.e. temperature, light intensity, humidity). Furthermore, plants release organic carbon into the sediments via litter, root exudates, and root turnover (Hale and Moore, 1979), which subsequently drives many biotic and abiotic reactions as the organic carbon is degraded and sediments become more reduced (Chanton and Dacey, 1991; Park and Jaffe, 1996; Park and Jaffe, 1999; El-Shatnawi, 2001). Microbial mediated degradation of organic matter affects processes of metal removal and mobilization including sedimentation, adsorption, complexation, and plant uptake in the sediments. As wetlands are considered as a effective sink for metals, recently, wetlands to purify wastewater have been constructed (Dunbabin and Bowmer, 1992). Therefore, a further investigation of how the presence of plants and their growth cycle affects the biogeochemistry of sediments will be of particular importance to understand the role of wetland in the ecological environment.

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< 국문적요>

퇴적물내의 산소와 물 수송에 관한 습지 식물의 역할

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습지를 규정하는 주요한 특징의 하나인 습지식물은 장기간의 침수로 인해 혐기성 상태로 존재하는 습지 퇴적물에서 생존을 위한 특별한 적응방법을 발달시켰다. 식물체내에 넓게 분포하고 있는 다공성의 세포는 공기중의 산소를 뿌리로 운반하기 위한 통로로 작용하며, 농도차이에 의한 확산과 압력차이에 의한 대류에 의하여 산소가 운반되어진다. 이러한 식물체 내에서의 산소이동은 식물이 혐기성 퇴적물 속으로 뿌리를 내리고 생존하게 하는 주요한 기작이 된다. 뿌리로 이동되어진 산소는 혐기성 퇴적물로 확산되어져서 뿌리주변의 퇴적물은 산화상태로 변화시키고, 뿌리의 호흡, 미생물의 호흡, 미생물에 의한 유기물 분해반응을 촉진시키게 된다. 또한 습지식물은 생장에 필요한 수분을 뿌리로 흡수하며, 이는 지표수와 퇴적물내 공극수가 뿌리주변으로 이동하게 되는 추진력이 된다. 습지 퇴적물은 식물의 사체에서 기인하는 유기물에 의해 수리학적 전도도가 작아서 퇴적물내 물의 움직임이 미미하나, 식물에 의한 물의 흡수는 퇴적물내 물의 움직임을 촉진시키게 된다. 이러한 식물의 특별한 적응기작은 해부학적, 형태학적, 생리학적으로 많은 연구가 수행되어져 왔으나, 이러한 적응기작들에 퇴적물내 생지화학적 반응에 미치는 영향에 대한 연구는 미비한 수준에 머물러있다. 퇴적물내 생지화학적 반응들은 수체에서 유입된 미량 오염물질의 이동 및 변형과정에 영향을 미치게 되므로 식물의 작용에 의한 생지화학적 반응의 변화들은 미량 오염물질의 거동에 영향을 미치게 되며 나아가 수자원과 수질 생태계에 영향을 초래하게 된다. 따라서 식물의 존재와 성장에 따른 퇴적물내 생지화학적 반응의 변화는 생태학적 환경에서 습지의 중요성을 인식하는데 필요한 연구과제라 사료된다.