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FUNCTIONS OF MACROPHYTES IN CONSTRUCTED WETLANDS

Hans Brix

Institute of Biological Sciences, Department of Plant Ecology, University of Aarhus,
Nordlandsvej 68, DK-8240 Risskov (Denmark)

ABSTRACT

Macrophytes have several intrinsic properties that makes them an indispensable component of constructed wetlands. The most important functions of the macrophytes in relation to the treatment of wastewater are the physical effects brought about by the presence of the plants. The macrophytes stabilise the surface of the beds, provide good conditions for physical filtration, prevent vertical flow systems from clogging, insulate against frost during winter, and provide a huge surface area for attached microbial growth. Contrary to earlier belief, the growth of macrophytes does not increase the hydraulic conductivity of the substrate in soil-based subsurface flow constructed wetlands. The metabolism of the macrophytes affects the treatment processes to different extents depending on the design of the constructed wetland. Plant uptake of nutrients is only of quantitative importance in low-loaded systems (surface flow systems). Macrophyte-mediated transfer of oxygen to the rhizosphere by leakage from roots increases aerobic degradation of organic matter and nitrification. The macrophytes have additional site-specific values by providing habitat for wildlife and making wastewater treatment systems aesthetically pleasing.

KEYWORDS

Macrophytes; hydraulic conductivity; physical processes.

INTRODUCTION

Wetlands are, as the word indicates, wet lands, with soils that are more or less water saturated, at least periodically. The plants growing in wetlands (often called wetland plants or macrophytes) are adapted to growing in water-saturated soils. It is thus an intrinsic property of wetlands that they are vegetated by wetland plants, but it is sometimes questioned if the macrophytes are needed in constructed wetlands.

In this paper some of the many functions macrophytes have in relation to the treatment of wastewater in constructed wetlands are described. It should, however, also be emphasised that the macrophytes have additional functions that are not related to the treatment of the wastewater which may be significant at specific sites. In large systems, the wetland vegetation may support a diverse wildlife, including birds, reptiles, etc. This may be important in regions where natural wetlands, and thereby the natural wetland habitat, has been destroyed at a high rate during the past century. Another point that is important especially for small systems serving single houses, hotels, etc., is the aesthetic value of the macrophytes. It is possible to select nice-looking wetland plants like the Yellow Flag (*Iris pseudacorus*) or Canna-lilies, and in this way make sewage treatment systems aesthetically pleasing.

MACROPHYTE ADAPTATIONS

The primary difference between water-saturated and well drained soils is the availability of oxygen. In well drained soils, the pore spaces are filled with air with a relatively high content of oxygen. Microorganisms living in the soil and roots of plants growing in the soil therefore are able to obtain oxygen directly from their surroundings. In a water-saturated soil, the pore spaces are filled with water, and because of the slow rate of oxygen diffusion in water, the water-saturated soils becomes anaerobic (oxygen-free or anoxic) except for a few millimetres at the surface. The root systems of plants growing in water-saturated substrates therefore must obtain oxygen from their aerial organs via transport internally in the plants.

Wetland plants are morphologically adapted to growing in a water-saturated sediment by virtue of large internal air spaces for transportation of oxygen to roots and rhizomes. The extensive internal lacunal system, which normally contains constrictions at intervals to maintain structural integrity and to restrict water invasion into damaged tissues, may occupy up to 60% of the total tissue volume depending on species. The internal oxygen movement down the plant serves not only the respiratory demands of the buried tissues, but also supplies the rhizosphere with oxygen by leakage from the roots. This oxygen leakage from roots creates oxidized conditions in the otherwise anoxic substrate and stimulates both aerobic decomposition of organic matter and growth of nitrifying bacteria.

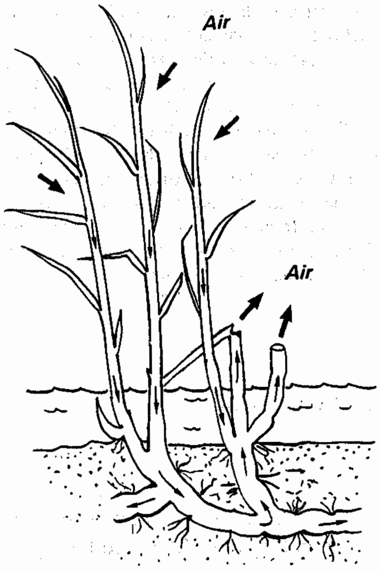

Fig. 1. Convective throughflow of gas in the Common Reed (*Phragmites australis*). Air enters the leaf-sheaths of green shoots against a small pressure gradient as a consequence of humidity-induced pressurization and thermal transpiration, passes down the culm to the rhizome, and up old dead or broken culms back to the atmosphere.

GAS TRANSPORT MECHANISMS IN WETLAND PLANTS

Internal transportation of oxygen in wetland plants may occur by *passive molecular diffusion* following the concentration gradients within the lacunal system, and by *convective flow* (i.e. bulk flow) of air through the internal gas spaces of the plants. In many wetland species convection plays a significant role in aeration of the below-ground tissues (Brix *et al.*, 1992). Convective flow of air in plants can be *throughflow* or *non-throughflow* (Armstrong *et al.*, 1991) and can be initiated by different physical processes. The convection can be driven by temperature and water vapour pressure differences between the inside of the plant tissue and the surrounding air by two purely physical processes known as *thermal transpiration* and *humidity-induced pressurization* (Brix, 1993). The air taken in from the atmosphere in one part of the plant is vented through rhizomes and back to the atmosphere through another part of the plant (Fig. 1). Convective throughflow can also be driven by gradients in wind velocity within a canopy by a process known as *venturi-induced convection*. This mechanism is based on the wind velocity being higher at higher positions in the canopy. In *Phragmites australis* the wind blowing across tall dead culms sucks atmospheric air into the underground root system via broken culms close to the ground level (Armstrong *et al.*, 1992). In contrast to humidity-induced and temperature- induced convection, which depend on specific porous structures within the plant tissue and gradients in water vapour pressure and temperature, venturi-induced convection can operate in damaged and dead plants and also during the night and winter, when water vapour and temperature gradients are small or lacking.

Exchange of gases between the gas spaces of buried plant tissues and the surrounding water may also lead to convective air flow inside the plant. This mechanism is based on the different solubilities of oxygen and carbon dioxide in water, carbon dioxide being approximately 30 times more soluble in water than oxygen. Solubilization of respiratory carbon dioxide has been shown to be able to produce some convective gas flow in wetland plants (e.g. *Carex gracilis*) (Koncalova *et al.*, 1988). Mathematical analyses have however demonstrated that this type of convection is subordinate to diffusion in the aeration process (Beckett *et al.*, 1988). The cause of this is that for every five oxygen molecules used by respiration, only one oxygen molecule is drawn in by convection, assuming all respiratory carbon dioxide is solubilized in the surrounding water. Further information on internal gas transport mechanisms in wetland plants can be found in Brix (1993) and Brix *et al.* (1992).

ROOT RELEASE OF OXYGEN

It is well documented that aquatic macrophytes release oxygen from their roots into the rhizosphere. Oxygen leakage to the rhizosphere is important in constructed wetlands with subsurface flow for aerobic degradation of oxygen-consuming substances and nitrification. Most studies on root oxygen release have been done using oxygen micro-electrodes to measure radial oxygen losses from individual roots in oxygen-depleted solutions (Armstrong, 1967; Laan *et al.*, 1989). The rates of oxygen release in wetland plants are generally highest in the sub-apical region of roots and decrease with distance from the root apex (Armstrong, 1979). Oxygen release from fine laterals at the base of roots can be significant, but generally, no release of oxygen from old roots and rhizomes is detected (Armstrong and Armstrong, 1988). The nonhomogeneity of the oxygen release pattern of wetland roots makes it difficult or impossible to extrapolate from results obtained by the oxygen micro-electrode technique to *in situ* release rates. Using different assumptions of root oxygen release rates, root dimensions, numbers, permeability, etc., Lawson (1985) calculated a possible oxygen flux from roots of *Phragmites* up to 4.3 g m^{-2} day^{-1}. Others, using different techniques, have estimated root oxygen release rates from *Phragmites* to be 0.02 g m^{-2} day^{-1} (Brix, 1990), 1-2 g m^{-2} day^{-1} (Gries *et al.*, 1990), and 5-12 g m^{-2} day^{-1} (Armstrong *et al.*, 1990). The wide range in these values is caused partly by the different experimental techniques used in the studies, partly by the seasonal variation in oxygen release rates.

Oxygen release rates from roots depend on the internal oxygen concentration, the oxygen demand of the surrounding medium and the permeability of the root-walls. Wetland plants conserve internal oxygen because of suberized and lignified layers in the hypodermis and outer cortex (Armstrong and Armstrong, 1988). These stop radial leakage outward, allowing more oxygen to reach the apical meristem. This characteristic of wetland plants to conserve internal oxygen is inconsistent with the concept of wastewater treatment in subsurface flow constructed wetlands. The wetland plants attempt to minimize their oxygen losses to the rhizosphere, whereas the concept of wastewater treatment implies a high oxygen leakage from roots. Wetland plants do, however, release oxygen from their roots. Leakage occurs primarily at the root-tip, and it serves to oxidize and detoxify potentially harmful reducing substances in the rhizosphere. Species possessing an internal convective through-flow ventilation system have higher internal oxygen concentrations in the rhizomes and roots than species relying exclusively on diffusive transfer of oxygen (Armstrong *et al.*, 1990). Furthermore, convective through-flow significantly increases the root length that can be aerated, compared to the length by diffusion alone. Wetland plants with a convective through-flow mechanism therefore have the potential to release more oxygen from their roots compared to species without convective throughflow. Thus, from the point of view of rhizosphere oxidation these species are superior in constructed wetlands. However, other factors such as rooting depth, tolerance to high loads of wastewater, plant productivity, etc., also have to be taken into consideration when considering the suitability of different plant species in constructed wetlands.

INFLUENCE ON SOIL HYDRAULIC CONDUCTIVITY

In constructed wetlands with subsurface horizontal water flow, the flow of water in the bed is intended to be largely subsurface through channels created by the living and dead roots and rhizomes, as well as through soil pores. As the roots and rhizomes grow they disturb and loosen the soil. Furthermore, when roots and rhizomes die and decay, they may leave behind tubular pores and channels (macropores), which are thought by some to increase and stabilize the hydraulic conductivity of the soil (Kickuth, 1981). The structure of the macropore system is dependent on the plant species and the conditions of growth, and can be very effective in channelling water through a bed of soil (Beven and Germann, 1982). Claims have been made that after a period of three years (three full growing seasons) any soil will develop a hydraulic conductivity of 10^{-3} m sec^{-1} and, once developed, the hydraulic conductivity will stabilize and maintain itself (Kickuth, 1981). Data concerning development of hydraulic conductivity in soil-based constructed reed beds in Austria, Denmark and the UK have, however, failed to prove this statement (Schierup *et al.*, 1990). On the contrary, the hydraulic conductivity often decreases and usually stabilizes in the range of 10^{-5} to 10^{-6} m sec^{-1}. Therefore, hydraulic dimensioning of constructed wetlands with subsurface flow should not be based on the assumption that the hydraulic conductivity will increase as a consequence of root and rhizome growth.

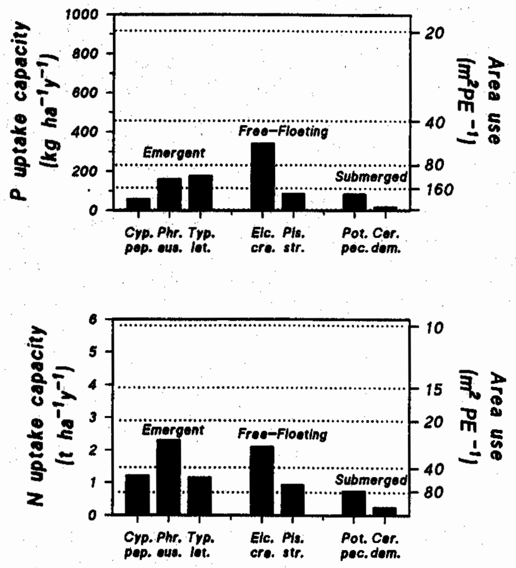

Fig. 2. Nutrient uptake capacities of a number of emergent (*Cyperus papyrus, Phragmites australis, Typha latifolia*), free-floating (*Eichhornia crassipes, Pistia stratioides*) and submerged macrophytes (*Potamogeton pectinatus, Ceratophyllum demersum*). On the right axis are the corresponding surface area (m^2 PE^{-1}) needed to rely exclusively on macrophyte removal of nitrogen (N) and phosphorus (P) listed (based on data from Rogers *et al.*, 1985).

PLANT UPTAKE OF NUTRIENTS

Wetland plants take up nutrients with their root systems. As wetland plants are very productive, considerable amounts of nutrients can be bound in the biomass. However, the amount is still insignificant compared to the loading into the constructed wetlands with the wastewater. In Fig. 2 are shown the amounts of nitrogen (N) and phosphorus (P) that can be taken up by a number of emergent, free-floating and submerged macrophytes, and thus the amount that can be removed if the biomass is harvested. The uptake capacity of emergent macrophytes is roughly in the range 50 to 150 kg P ha^{-1} $year^{-1}$ and 1000 to 2500 kg N ha^{-1} $year^{-1}$. The highly productive water hyacinths have generally higher uptake capacities whereas the capacity of submerged macrophytes is lower. Figure 2 also shows the surface area of wetland needed to rely exclusively on macrophyte uptake for nutrient removal. It is seen that, even for water hyacinths, an area of 30-50 m^2 PE^{-1} is needed.

TABLE 1. Relative Importance of the Macrophytes in Different Designs of Constructed Wetlands. Number of +'s Increases with Importance of the Process; "-" Designates No Importance

	Surface Flow	Subsurface Flow	Vertical Flow	Combined Systems
Area use	>20 m^2/PE	~10 m^2/PE	~5 m^2/PE	2-5 m^2/PE
Stabilize bed surface	+++++	+++++	+++	+++
Prevent clogging	-	-	+++++	+++++
Reduce current velocity	+++	-	-	-
Attenuate light	+++++	++	+	+++
Insulation	+++	+++	+++	+++
Attached microbes	+++++	+++	+	+
Uptake of nutrients	+++++	+	-	+
Oxygen transfer & release	+	++	+	+
Habitat for wildlife	+++++	+++	+	+
Aesthetics	+++++	+++++	+++	+++++

OTHER MACROPHYTE FUNCTIONS

Wetland plants have several other properties which influence the treatment of wastewater in constructed wetlands. The importance of the different properties varies according to the concept/design of the constructed wetland. Summarized in Table 1 are the relative importance of the macrophytes in surface flow wetlands, subsurface horizontal flow wetlands, vertical flow wetlands, and combined systems. Surface flow constructed wetlands typically consist of trenches or basins with emergent macrophytes and free water on the surface (water depth 30-40 cm). Subsurface horizontal flow systems are rectangular beds planted with emergent macrophytes and, ideally, have no water on the surface. The medium which the wastewater has to pass through horizontally may be soil or gravel. In vertical flow systems the wastewater is led onto the surface of a planted bed from where it percolates through the medium (usually fine sand) to a drainage system located in the bottom of the bed. In combined systems several horizontal subsurface flow and vertical flow systems are operating in series, which intensifies the treatment processes and therefore reduces the surface area requirements. A more detailed description of the different concepts can be found in Brix and Schierup (1989) and Brix (1991).

The presence of macrophytes is important for stabilizing the bed surface in all systems, and especially in surface flow and subsurface horizontal flow systems. Their root systems stabilise the surface of the soil and prevent the formation of erosion channels. In vertical flow systems the macrophytes prevent clogging of the medium. The presence of the plants and their movement as a consequence of wind, etc. keeps the surface open and thus helps preventing clogging. In surface flow systems the vegetation reduces the water current velocity and thereby creates better conditions for sedimentation of suspended solids.

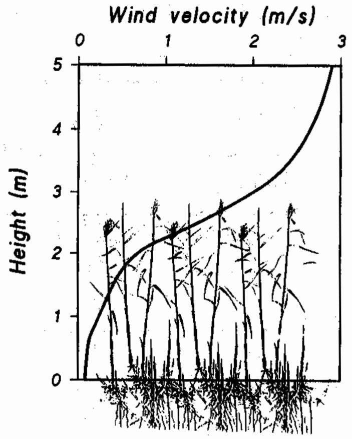

Fig. 3. Effect of a dense canopy of *Phragmites australis* on the wind velocity. Wind velocity is reduced in the canopy restricting wind induced turbulence and thereby resuspension of settled material in the water.

The vegetation of macrophytes in a constructed wetland can be regarded as a huge biofilm, and gradients in different environmental parameters occur within this biofilm. Wind velocities are reduced (Fig. 3), which might be of importance in surface flow wetlands, as resuspension of settled material is thereby decreased. However, gas exchange is diminished by slow air movement, which may not be desirable from the point of view of wastewater treatment. Light is attenuated, hindering production of algae in open-water channels (Fig. 4). This property is used in duckweed-based systems, as algae die and settle out beneath the dense cover of duckweeds (Ngo, 1987). Another important effect of the plants is the insulation that the cover provides during winter (Figs. 5 and 6). When the dead, still-standing plant material is covered by snow it provides an effective insulation and helps keep the bed medium free of frost.

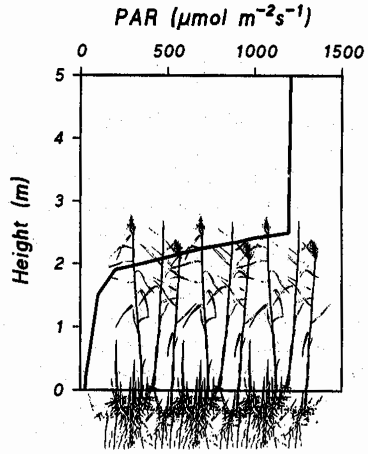

Fig. 4. Effect of a dense canopy of *Phragmites australis* on the incident light intensity. The vegetation effectively shade out algae in the water beneath the canopy.

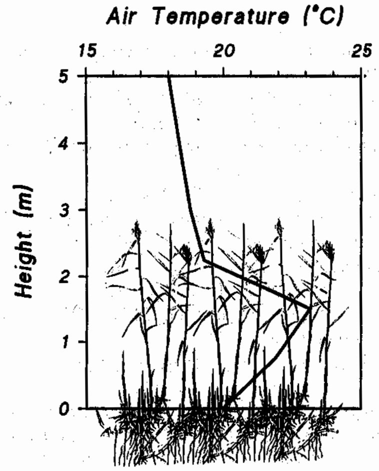

Fig. 5. Effect of a dense canopy of *Phragmites australis* on the air temperature during summer. Air temperature within the canopy is higher because of absorption of solar radiation.

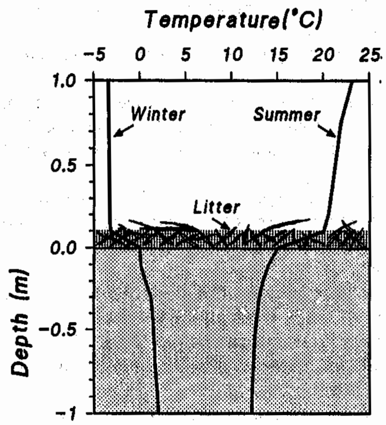

Fig. 6. Effect of the litter layer within a stand of *Phragmites australis* on the soil temperature during winter and summer, respectively. The litter layers insulates the soil and helps protecting the soil from freezing during winter. On the other hand, the litter layer keeps the soil cooler during summer.

CONCLUSIONS

In conclusion, macrophytes have several properties in relation to the treatment processes in constructed wetlands that make them an indispensable component of constructed wetlands. The most important effects of the macrophytes in relation to the wastewater treatment processes are the physical effects the plant tissues give rise to (e.g. erosion control, filtration effect, provision of surface area for attached microorganisms). The metabolism of the macrophytes (plant uptake of nutrients, oxygen release, etc.) affects the treatment processes to different extents depending on design. The macrophytes have other, site-specific, valuable functions, such as providing a suitable habitat for wildlife, and giving systems an aesthetic appearance. So, the answer to the question: "Do we need the macrophytes in the constructed wetlands?" is definitely: "Yes".

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