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Wetland plants – more than just a pretty face?

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Abstract

Plants are an integral part of wetlands constructed to treat contaminated waters, including those emanating from abandoned mines and their associated spoil heaps. It has become generally accepted that, although plants provide an aesthetic covering to wetlands, they do not play an important role in the remediative processes that occur within the wetland system. Rather the geochemical and microbiological processes that convert soluble metals into immobile forms are by far the most important constituents of the wetlands. We have provided a detailed review of the current knowledge of plant growth within wetlands and the possible roles that they perform in the treatment of mine waters. It is evident from the literature that plants add significantly to the performance of wetland systems through a variety of means. These include the addition of organic matter (maintaining the carbon source for microorganisms), stabilisation of sediment surfaces, maintenance of flow patterns, and surfaces for microbial activity. In addition, recent research has shown that in systems receiving low concentrations of metals, as occurs in 'polishing wetlands', plants may actually constitute an important sink for metals. In this situation the majority of metals (iron, manganese and aluminium) are precipitated around root surfaces as plaque deposits, which has important implications for the cycling of metals within these systems. Finally, plants may also provide a vital resource for other wildlife and as such can encourage the inhabitation of treatment wetlands by invertebrates, birds and mammals. Thus plants as part of treatment wetlands are certainly more than just a pretty face.

Key words: aesthetic value, ancillary benefits, metal removal, organic matter, treatment, wetland plants, wetlands

INTRODUCTION

The success of constructed wetlands in improving water quality of both acidic and circum-neutral mine discharges is well documented (e.g. Younger *et al.* 1997; Jarvis and Younger 1999; Laine 1999; Younger *et al.* 2002). The dominant processes of metal removal that have been identified in such systems are predominantly biogeochemical and include metal reduction, oxidation, hydrolysis and formation of carbonates and sulphides. As a result, the majority of research has concentrated upon the relative importance of these processes within different treatment situations. However, wetland plants (often termed macrophytes) are also an intrinsic component of these systems. In more recent years, wetland plants have suffered somewhat from 'bad press', and their role within wetland systems has now been relegated to that of aesthetic value. Although undoubtedly plants can significantly enhance the scenic value of constructed wetlands, it is also possible that they can play an important role in the removal of metals from contaminated waters, both directly and indirectly. This paper aims to provide a comprehensive review and evaluation of emergent macrophyte growth in treatment wetlands and their significance in the performance of these systems.

WETLAND PLANTS

Wetlands by definition are areas that possess soils that are water saturated at least periodically. As such the soils are characterised by anaerobic conditions, as oxygen becomes deficient within a few centimetres of the soil surface, due to the very slow diffusion of oxygen in water, which may be up to 10 000 times slower than in

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air (Armstrong 1978). Once flooded, any oxygen that may be present in the soil is rapidly consumed by the metabolism of microbes and chemical oxidation. As the oxygen is consumed, anaerobic micro-organisms utilise a series of alternative electron acceptors during respiration, which include such oxidised components as nitrate, manganese dioxide, hydrated oxides of iron (III) and sulphate (Ponnamperuma *et al.* 1967). This process produces an overall reduction in the redox potential of the soil. As a result of this, the reduced forms of compounds can be released into soil solution, which may then be more bioavailable to plants, possibly to toxic levels.

The growth of plants within wetlands is dependent upon a number of adaptations to these distinctive characteristics of the environment. Due to the anoxic nature of the soil, oxygen requirements of the roots must be met by the movement of oxygen from the aerial parts of the plant (shoots and leaves) to the subaerial parts (roots and rhizomes). The development of lacunae and/or aerenchyma is a characteristic of non-woody species which can increase the porosity of the plants by as much as 60% (Armstrong 1976). This allows movement of oxygen to the root zone, which has been measured at a rate of between 2.08 g O_2 m^2 d^{-1} (Brix and Schierup 1990) and 5 to 12 g O_2 m^2 d^{-1} in the species *Phragmites australis* (common reed). The movement of air down these pathways is achieved through gas-phase convection and/or diffusion but may be enhanced through convective flow driven by humidity and temperature gradients (Armstrong and Armstrong 1988, 1990*a*,*b,* 1991; Armstrong *et al.* 1992). The presence of the root exodermis prevents the loss of oxygen from the roots to some extent, but oxygen is still able to diffuse out into the anaerobic sediment, particularly from young, adventitious, secondary roots and basal regions of laterals (Armstrong and Armstrong 1988). This diffusion of oxygen has been termed 'radial oxygen loss' (ROL). Some species may also develop very shallow root systems in order to exploit the relatively oxygen rich upper layers of the soil (Black 1968) but this tends not to be the case for those species typically used in treatment wetlands, e.g. *Phragmites australis, Typha latifolia, Iris pseudacorus* and *Scirpus lacustris.*

The reduced nature of the soil also means that many compounds may be in their reduced form and thus potentially more bioavailable for uptake by plants. These can include many essential elements for plant growth, such as iron, manganese, copper, nickel and phosphorus (released on the reduction of iron oxides). This can provide an adequate supply of nutrients that may be limiting in other environments. However, in some cases the mobilisation of these elements can result in concentrations within soil solutions that may be phytotoxic to plants and other organisms. This problem is accentuated in treatment wetlands designed for mine drainage as, by definition, the waters entering the wetland contain elevated concentrations of metals such as iron, manganese and aluminium. This can result in a growth environment that could be extremely toxic to the biota. A number of adaptations have been proposed that may enable some species to grow under such hostile conditions. The first of these is the formation of iron (oxyhydr-) oxide coatings around the roots of plants which have generally been termed 'iron plaques'. These plaques can be identified as an orange-brown deposit on the root surface. The exact cause of the precipitation of such deposits around roots remains unclear, but appears to include a combination of radial oxygen loss where the oxygen reacts with reduced iron in the surrounding rhizosphere and precipitates on the root surface; release of exudates, including enzymes, from the roots themselves (Yamada and Ota 1958); and the presence of microorganisms (e.g. Crowder *et al.* 1987; St-Cyr *et al.* 1993; Hansel *et al.* 2001; Neubauer *et al.* 2002). Iron plaques have been reported to consist of lepidocrocite (γ-FeOOH) (Bacha and Hossner 1977), a mixture of lepidocrocite and goethite (α-FeOOH) (Chen *et al.* 1980*a*; St-Cyr *et al.* 1993) and ferric phosphate (Snowden and Wheeler 1995). Iron, however, is not the only element that can form plaques. Manganese oxide plaques have also been identified both in the presence and absence of iron plaques (e.g. St-Cyr and Crowder 1990; Crowder and Coltman 1993; St-Cyr and Campbell 1996; Batty *et al.* 2002). Aluminium has also recently been identified as forming a plaque deposit composed of aluminium phosphate (Batty *et al.* 2002). Root plaques may also contain a variety of metals and metalloids, including arsenic, cadmium, mercury, nickel, lead and zinc (Otte *et al.* 1987, 1989, 1995; St-Cyr and Crowder 1987; St-Cyr and Crowder 1990; Greipsson and Crowder 1992; St-Cyr and Campbell 1996; Doyle and Otte 1997; Ye *et al.* 1997; Sundby *et al.* 1998; Ye *et al.* 1998*a*). Phosphorus has also been identified with plaque deposits (Snowden and Wheeler 1995; Batty *et al.* 2000). It is the presence of these additional elements that led to the proposal that the formation of root plaques could immobilise and prevent the uptake of potentially phytotoxic metals. However, this role of plaques as an adaptation to the environment remains controversial. Although this 'exclusion' hypothesis is supported by the amelioration of toxic effects of metals within a variety of species (Greipsson and Crowder 1992; Crowder *et al.* 1987), conflicting results have been reported which demonstrate that the presence of plaque does not enhance metal tolerance or plant growth (Ye 1995; Ye *et al.* 1997*a*,*b*, 1998*a*). Quantitative data on the uptake of metals is also conflicting. Some research has shown that plaques may act as a filter for metal movement into rhizomes and shoots for iron, copper, zinc, nickel and cadmium (Greipsson and Crowder 1992; Greipsson 1994; Wang and Peverly 1995). In contrast, the majority of research has shown that the formation of plaque does not impede the uptake of toxic metals (Benckiser *et al.* 1984; Levan and Riha 1986; St-Cyr and Crowder 1987; Crowder and Coltman 1993; Ye *et al.* 1997*a* 1998*a*). It has since been suggested (Batty *et al.* 2000) that although plaques may reduce metal uptake into the plant tissues, they do not prevent it. This is supported by data obtained from the field where, although iron plaques were observed and measured on the roots of plants, the shoots still contained elevated concentrations of metals, which in some cases were at levels that would normally be considered toxic (Table 1).

Table 1. Metal concentrations in shoots of wetland plant species in mg kg^{-1} dry wt. Sample collection sites were [a] Parys Mountain, Anglesey, UK and [b] Woolley Colliery, Yorkshire, UK. For further details of sample collection and analysis refer to Batty (1999)

	Phragmites australis	*Typha latifolia*	*Eriophorum angustifolium*
Fe	35 677[a] 1974[b]	19 348[b]	38 558[a]
Mn	169[a] 446[b]	1956[b]	111[a]
Zn	378[a] 37[b]	28[b]	300[a]
Al	71[a] 3[b]	81[b]	325[a]
Cu	70[a] 28.7[b]	13[b]	205[a]
Pb	191[a]	–	595[a]

The method by which wetland plants growing in wetlands receiving high concentrations of metals are able to survive remains unclear. It has been proposed that high levels of iron within leaves enables the competition of iron with other elements (e.g. copper) for sensitive metabolic sites (Greipsson 1994). However, in many cases, such as those presented in Table 1, iron concentrations in leaves are themselves significantly higher than those normally considered to constitute toxicity in wetland plants (1100–1600 mg kg^{-1} dry wt (Marschner 1995)). It is possible that metals are being sequestered away from sensitive sites in the leaves, but this has not been proven.

In addition to the normal stresses that occur in a wetland environment, plants growing in treatment wetlands may also have to deal with added problems that need additional adaptation in order to allow normal growth to continue. The chemical characteristics of mine waters are such that in the majority of cases concentrations of essential plant nutrients such as nitrate and phosphate are extremely low. Concentrations of phosphate in spoil heap discharge entering the treatment wetland at Quaking Houses in County Durham were lower than detection limits (<0.1 mg L^{-1}) (Batty, unpublished data). Therefore it is possible that plants growing within treatment wetlands could suffer from nutrient deficiencies, and it has been postulated that this may be the cause of some wetland failures (Younger pers. comm.). It has been suggested that the presence of phosphate and other elements within root plaque deposits may act as a reservoir for those essential elements (Trolldenier 1988; Conlin and Crowder 1989) which could then be remobilised in times of deficiency. However, this suggestion depends on nutrients being present and available to plants in sufficient concentrations at some time prior to times of deficiency, which may not be the case in some treatment wetlands.

Finally, it is important to note that in some cases failure of treatment wetlands may be due not to the toxicity of metals or to nutrient deficiencies, but instead related to the maintenance of water levels within the wetland system. Not only is it important to maintain levels to within a few centimetres in order to maintain flow and therefore residence time within the system, levels must also be kept to a maximum of 0.5 m, particularly in the spring when new growth of reeds is emerging. This is essential, for, above this level, growth of plants may be inhibited, as the new shoots remain submerged for too long a period (Coops and Van der Velde 1995).

THE ROLE OF PLANTS IN TREATMENT WETLANDS

The specific qualities and adaptations that some wetland plant species possess has led to their extensive use in vegetating treatment wetlands designed for the remediation of mine waters, particularly those that are net alkaline. The main species that have been used in such systems are *Iris pseudacorus* (yellow flag iris), *Juncus effusus* (soft rush), *Phalaris arundinacea* (reed canary grass), *Phragmites australis* (common reed), *Scirpus lacustris* (common club rush) and *Typha latifolia* (reed-mace). All these species show rapid growth and a tolerance of elevated metal concentrations in their growing environment. The use of these species is not consistent, the most common species used in Europe being *P. australis*, whereas that most often seen in North American systems is *T. latifolia.* In addition, species may be planted within systems as a monoculture, or alternatively the design of the wetland is such that it allows a number of species to be planted as a diverse ecosystem (e.g. Quaking Houses, Co., Durham, UK).

It has become the general opinion of workers in this field that the plants themselves do not constitute an important sink for metals within treatment wetlands. Although, as stated above, plants do take up a significant amount of metals into their tissues, this is not considered to be important on the scale of the wetland as a whole. For instance, *T. latifolia* has been shown to remove less than 1% of the total iron entering a wetland system (Sencindiver and Bhumbla 1988). However, the presence of vegetation has been shown to improve the removal of contaminants in experimental systems (e.g. Wolverton *et al.* 1983). Iron removal efficiency at Woolley Colliery (West Yorkshire, UK) was also shown to improve from 70%, when first planted, to >95%, once the vegetation had become mature (Younger *et al.* 2002). A number of effects of plants within wetlands have been proposed which could contribute to their importance in reaching and maintaining high removal efficiencies.

The growth of roots and rhizomes affects the subaerial environment by disturbing the soil. Upon death of roots and rhizomes, which is a continual process during the lifetime of the plant, the pores and channels that mark their position may remain, which could increase the hydraulic conductivity of the soil (Beven and Germann 1982).

The presence of roots may also affect the chemistry of the wetland substrate, although the zone of influence tends to be confined to the rhizosphere which extends only a few millimetres from the root surface. However, the total surface area of the anaerobic–aerobic plane around rhizospheres in densely vegetated wetlands can be much larger than the area of the horizontal sediment–water/anaerobic–aerobic interfaces (e.g. Francour and Semroud 1992). Roots release a number of substances from their roots that may include oxygen, enzymes, allelopathic chemicals and antibacterial agents. Many of these can affect the rhizosphere directly by altering the pH and oxidative status of the environment, and indirectly by encouraging or discouraging the growth of bacteria, algae and higher organisms that could in turn affect the chemistry of the environment by their activity. We have seen already how root exudates can cause the precipitation of iron, manganese and aluminium plaques around the roots of the wetland plants. The concentration of metals in these deposits can be extremely high, and some examples are given in Table 2.

Although this has previously been considered to be an unimportant sink for metals when considered on the scale of the wetland as a whole, recent research has suggested that this may not be the case in all situations. Laboratory experiments carried out on the species, *P. australis,* demonstrated that when iron was supplied at a concentration of 1.0 mg L^{-1} almost 100% of the iron supplied was taken up by the plant. At concentrations above this, the removal efficiency of the plant decreased rapidly and was less than 5% when iron was supplied at 50 mg L^{-1} (Batty and Younger 2002). This data suggests that the removal of metals by wetland plants may be a far more important process than has previously been considered in wetlands receiving lower concentrations of metals, as is increasingly the case where they are used as a final ‘polishing’ process of mine waters. This could have important implications for the cycling of metals within wetland systems, and in particular the potential release of metals back into the system during the dormant season, or upon death of plant parts as part of the natural life cycle. However, although metals are taken up into the aerial parts of the plant, the majority are found concentrated in plaque deposits at the root surface. Therefore the annual turno-

Table 2. Concentrations of metals in root plaque extracts in field grown wetland plant species

Plant species	Metal	Concentration in root plaque (mg kg^{-1} dry wt)	Reference
Eriophorum angustifolium	Iron	41 090	Batty 1999
Phragmites australis	Iron	Up to 10 000 (ppm)	St-Cyr and Crowder 1988
Phragmites australis	Iron	159–10 433	St-Cyr and Crowder 1989
Phragmites australis	Iron	395–1211	Wang and Peverly 1996
Phragmites australis	Iron	54836	Batty 1999
Typha latifolia	Iron	2550–62 922	Macfie and Crowder 1987
Typha latifolia	Iron	Up to 30 000	Ye *et al.* 1998
Typha latifolia	Iron	64 818	Batty 1999
Vallisneria americana	Iron	8080–187 000	St-Cyr and Campbell 1996
Phragmites australis	Manganese	20–4323	St-Cyr and Crowder 1990
Phragmites australis	Manganese	6691	Batty 1999
Phragmites australis	Lead	7795	Batty 1999

ver of leaves and shoots is unlikely to contribute a significant source of metal release upon decomposition. The turnover of plant roots is slower than that of shoots, although the time involved varies with species, it is on average every two years rather than every year for shoots. Upon death the roots will already be within the overall reducing environment and so it is likely that any metals released as a result of root death and decomposition will be reduced and sequestered as sulphides, thus preventing significant remobilisation of metals.

Within compost wetlands, the presence of a carbon source has been shown to be important in providing a food source for the bacteria, that are responsible for the key processes of sulphate reduction involved in the immobilisation of metals. The carbon source is initially provided through the inclusion of organic matter within the substrate of the wetland. This is often in the form of spent mushroom compost, cow or horse manure (e.g. Younger *et al.* 1997). However, over time this carbon material will gradually be depleted by bacteria, and so for the wetland to continue to function, carbon needs to be replenished within the wetland. The primary way that this occurs is through the annual turnover of plant leaves and shoots. In addition, enzymes released into the rhizosphere by plant roots can continue to function long after the death of the root and these enzymes can enhance the breakdown of organic matter (Neori *et al.* 2000). Thus plants can be an essential part of the long-term functioning of the wetland.

The presence of vegetation can also improve the stability of the bed surface of a wetland system, particularly in those designed with a horizontal flow system. The root systems of plants stabilise the surface of wetland soils, so preventing erosion of the surface, particularly during periods of high flow, and also prevent the formation of preferential flow patterns, so maintaining the overall flow volume and thus the residence time of the water. In addition, the baffling of the flow by the presence of plants slows the water and so encourages the settling of suspended solids. The resuspension of such solids is also prevented by wetland plants as they can reduce wind velocity close to the surface of the water, which in turn restricts the development of water turbulence (Brix 1994).

The contributions outlined here that plants give to a wetland have concentrated on their importance in the functioning of wetlands as a facility that improves water quality. The importance that plants play in the ancillary benefits of such systems must not be ignored. Increasingly it is becoming recognised that wetlands designed for the treatment of mine waters (and other contaminated discharges) can be an important resource for wildlife, and as such the designs of such systems are beginning to incorporate features that will maximise this benefit. One of these design features is the planting of wetlands not only with a variety of species other than the monoculture that is traditionally used, but also species that are native to the region where the wetland is located. This has led to the development of wetlands that have become important resources both for wildlife and for the local community. The presence of vegetation encourages the inhabitation of the wetland with a wide variety of invertebrates, which in turn may provide an important food source for local bird populations. It should be noted that many of the wetlands used in water treatment are too small to support large populations of birds and mammals, particularly those that have large home ranges (Hawke and José 1996).

Plants have undeservedly been ignored as a key component of treatment wetlands. Not only do they add considerably to the aesthetic value of a wetland but they also contribute in many ways to its ability to improve water quality. This may help to explain why, in some cases, treatment systems have over-performed in terms of metal removal when the design was based on chemical processes (Batty and Younger 2002). Thus plants and their place in the wetland ecosystem should be an important consideration in the future design of treatment systems, particularly in those that will constitute a final ‘polishing’ process in the remediation of mine water.

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