Seasonal plant effects on wastewater treatment and root-zone oxidation in model wetlands
by Winthrop Coffin Allen

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University

Abstract:
Constructed wetlands can improve water quality for a variety of wastewaters, but there is little information regarding treatment performance in cold regions. Plants can improve performance through their influence on oxygen-dependent or redox-sensitive transformations of pollutants. Additional information is needed on the effects of plants on seasonal performance and there is a need to investigate additional plant species for use" in constructed wetlands. Effects of Carex rostrata, Scirpus acutus, and Typha latifolia on removal of C, N, and P and root-zone oxidation were compared over 18 months. Mature plants were transplanted from field sites to gravel-filled 20X60 cm cylinders in a greenhouse. Following eight months for establishment and wastewater acclimation; nutrient removal, redox potential (Eh), and sulfate concentrations were monitored during 20-day incubations of simulated secondary wastewater at temperatures ranging from 4°C to 24°C, changing in 4°C steps. Results for the final year of the study showed distinct treatment and seasonal patterns in nutrient removal and root-zone oxidation that were not observed or were weaker in earlier incubations; long-term trends were apparently related to system development.

Seasonal patterns for nutrient removal and root-zone oxidation were distinct, but all were affected by plants and differed among species. All plants enhanced removal of chemical oxygen demand (COD), total nitrogen (IN), and PO4^3- (C. rostrata > S. acutus > T. latifolia > unplanted control), but treatment effects varied seasonally and differences among species were generally larger in cold than warm periods. C. rostrata and S. acutus increased Eh values and SO4^2- concentrations, particularly in cold periods. Low temperatures decreased COD removal in T. latifolia columns and unplanted controls, but removal increased at low temperature with C. rostrata and S. acutus. Low temperature decreased TN and PO4^3- removal with all plant species, but C. rostrata clearly showed superior cold season performance. Some seasonal differences in nutrient removal among plant species appeared to be related to species' different abilities to increase root-zone oxygen supply.

The relatively effective wastewater treatment seen at low temperatures with C. rostrata and S. acutus suggests that subsurface flow wetlands can potentially operate successfully at low temperatures. Differences in nutrient removal and root-zone oxidation among plant species were greatest at low temperatures, during plant dormancy. Consequently, plant selection may be particularly important in cold regions.

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Constructed wetlands can improve water quality for a variety of wastewaters, but there is little information regarding treatment performance in cold regions. Plants can improve performance through their influence on oxygen-dependent or redox-sensitive transformations of pollutants. Additional information is needed on the effects of plants on seasonal performance and there is a need to investigate additional plant species for use in constructed wetlands. Effects of *Carex rostrata*, *Scirpus acutus*, and *Typha latifolia* on removal of C, N, and P and root-zone oxidation were compared over 18 months. Mature plants were transplanted from field sites to gravel-filled 20X60 cm cylinders in a greenhouse. Following eight months for establishment and wastewater acclimation, nutrient removal, redox potential (Eh), and sulfate concentrations were monitored during 20-day incubations of simulated secondary wastewater at temperatures ranging from 4°C to 24°C, changing in 4°C steps. Results for the final year of the study showed distinct treatment and seasonal patterns in nutrient removal and root-zone oxidation that were not observed or were weaker in earlier incubations; long-term trends were apparently related to system development.

Seasonal patterns for nutrient removal and root-zone oxidation were distinct, but all were affected by plants and differed among species. All plants enhanced removal of chemical oxygen demand (COD), total nitrogen (TN), and PO_4^{3-} (*C. rostrata* > *S. acutus* > *T. latifolia* > unplanted control), but treatment effects varied seasonally and differences among species were generally larger in cold than warm periods. *C. rostrata* and *S. acutus* increased Eh values and SO_4^{2-} concentrations, particularly in cold periods. Low temperatures decreased COD removal in *T. latifolia* columns and unplanted controls, but removal increased at low temperature with *C. rostrata* and *S. acutus*. Low temperature decreased TN and PO_4^{3-} removal with all plant species, but *C. rostrata* clearly showed superior cold season performance. Some seasonal differences in nutrient removal among plant species appeared to be related to species' different abilities to increase root-zone oxygen supply.

The relatively effective wastewater treatment seen at low temperatures with *C. rostrata* and *S. acutus* suggests that subsurface flow wetlands can potentially operate successfully at low temperatures. Differences in nutrient removal and root-zone oxidation among plant species were greatest at low temperatures, during plant dormancy. Consequently, plant selection may be particularly important in cold regions.

CHAPTER 1

INTRODUCTION

Constructed wetlands are widely used in wastewater treatment systems and can provide low cost, low maintenance alternatives to conventional technologies, but there is little practical information regarding their use in cold regions. Chemical, physical, and biological processes in wetlands can improve water quality for a variety of wastewaters (Reed 1995, USEPA 1993). However, design guidelines are inconsistent and performance of existing systems varies with site-specific differences in climate, hydrology, loading rate, and wastewater composition (Brix 1994, Reed and Brown 1992). Better understanding of treatment processes is necessary to evaluate feasibility for specific environments and wastewaters, optimize design and management, and to estimate long-term performance capabilities (Breen 1990, Howard-Williams 1985).

High priority research topics for subsurface flow constructed wetlands identified by the United States Environmental Protection Agency include: (1) temperature and seasonal effects on wastewater treatment, (2) the role of plants in providing oxygen for root-zone processes, (3) investigation of additional plant species suited for use in treatment wetlands, and (4) the use of drain and fill, batch-load operation (USEPA 1993). Subsurface flow wetlands usually consist of a shallow, lined channel filled with gravel or washed stone and planted with emergent macrophytes; water level is maintained below the gravel surface.

Experience with constructed wetlands in cold climates is limited but indicates that effluent criteria can be met with properly designed systems, and that temperature effects may be less than expected (Jenssen et al. 1993, Kadlec and Knight 1996, Wittgren and Maehlum 1997). There is little information on the effects of plants on seasonal performance of treatment wetlands and on differences among plant species.

Wetlands can successfully remove C, N, and P from wastewater and nutrient removal pathways include sorption to soil and organic surfaces, plant assimilation, sedimentation, precipitation, and microbial transformations (Brix 1994, Kadlec and Knight 1996, Reed 1995, USEPA 1993). Net removal of nutrients from the wastewater reflects the balance of removal processes and return fluxes from storage components (Breen 1990, Howard-Williams 1985). Sorption may buffer systems against short-term instability, but stored nutrients can later be released into solution (Brix 1987). Long term removal of pollutants occurs through sediment accumulation, precipitation reactions, and atmospheric losses of gaseous products (Howard-Williams 1985).

Plant and microbial processes involved in biological treatment are strongly influenced by temperature and other environmental factors that vary seasonally. Although effluent criteria can be met for subsurface flow wetlands in cold climates, operational systems do not show consistent seasonal patterns of nutrient removal (Gumbricht 1992, Hill and Payton 1998). The lack of significant temperature effects for subsurface flow wetlands has been attributed to the role of sedimentation, temperature adaptation of microbes, variation in decomposition rates of detritus, and thermal protection provided by plant litter, snow, and the subsurface position of the water (Kadlec and Knight 1996, Wittgren and Maehlum 1997).

Many studies have shown that wetland plants enhance wastewater treatment, but the relative magnitude of plant influences are debated (Burgoon et al. 1995, Gersberg et al. 1986, Rogers et al 1991, Wolverton et al. 1983). Plant influences include nutrient uptake, facilitation of gas exchange between sediments and the atmosphere, and alteration of microbial activity through the provision of attachment sites, exudates, and aerobic microenvironments (Brix 1997). These influences are likely to vary with site conditions and seasonal patterns of plant growth and senescence, which influence oxygen supply and nutrient uptake, allocation, and release (Callaway and King 1996, Howes and Teal 1994, Nichols 1983, Tanner et al. 1995)

Plant uptake of nutrients on an annual basis generally represents a small percentage of nutrients removed from wastewater, and some nutrients stored in plant tissues are later returned to the wastewater through decomposition processes (Brix 1997, Gersberg 1986, Kadlec and Knight 1996, Reed 1995). However, plant growth patterns influence seasonal nutrient uptake and plant uptake can be significant during the main growth period (Tanner 1995). Uptake is particularly important in immature systems before plant establishment and decomposition processes reach steady state (Breen 1990, Crites and Tchobanoglous 1992, Rogers 1991). Harvesting plants has been proposed to enhance nutrient removal, but aerial shoots represent as little at 33% of total nutrients stored by plants and plants are generally not harvested from operational systems (Crites and Tchobanoglous 1992, Rogers 1991).

Plant roots provide exudates and surfaces for microbial attachment, and may leak sufficient oxygen to influence root-zone oxidation and biogeochemical processes (Brix 1997). Provision of substrate for microbial growth and transmission of oxygen is believed to be the primary role of plants in subsurface flow wetlands (Reed and Brown 1992). In some plants, aerenchyma facilitates transport of O_2, N_2, and CH_4 between above-ground shoots and below-ground roots and rhizomes (Burgoon et al. 1995, Howes and Teal 1994). Oxygen release from plant roots is shown clearly by the reddish color of oxidized iron on the surfaces of some plant roots (Mendelssohn 1995). Radial oxygen loss from plant roots can be sufficient to support aerobic microbial activity (Barko et al. 1991, Boon and Sorrell 1991, Flessa and Fischer 1992) and may represent as much as 90% of the total oxygen entering wetland substrates (Reddy et al. 1989). However, the magnitude of oxygen flux from whole root systems is debated, and its evaluation is complicated by measurement issues, spatial heterogeneity, species differences, and seasonal differences in oxygen release (Armstrong and Armstrong 1988, Bedford et al. 1991, Howes and Teal 1994, Sorrell and Armstrong 1994). Oxygen demand for root and microbial respiration declines at cold temperatures, and lower oxygen demand may increase the potential for plants to oxidize the root-zone and affect redox sensitive processes (Callaway and King 1996, Howes and Teal 1994).

Plant influences on wastewater treatment vary among species and differences among species vary seasonally (Burgoon 1991, Reddy and DeBusk 1985). There is not a consensus on species selection, and Reed and Brown (1992) recommend investigation of additional plant species. Differences in plant tissues, metabolism, and oxygen transport mechanism affect plants' abilities to transport oxygen into the root zone (Armstrong and Armstrong 1990, Bodelier et al. 1996, Reddy et al. 1989, Steinberg and Coonrod 1994). Root density and distribution can affect oxygen supply, and species effects on wastewater treatment may be correlated to depth of rooting (Gersberg 1985, Moorhead and Reddy 1988). Differences in plant productivity also influence nutrient uptake and rates of organic matter accumulation.

The purpose of this study was to evaluate seasonal variability and temperature dependence of wastewater treatment in subsurface flow wetlands planted with different plant species. The objectives were: (1) to quantify seasonal variation in removal of C, N, and P in model subsurface flow wetlands, (2) compare performance of three plant species and unplanted controls across seasons, and (3) investigate the role of plants in providing oxygen for root-zone biogeochemical processes. The batch incubations used also provided information relevant to drain and fill, batch-load operation of SF wetlands.

Batch incubations were conducted approximately monthly from December 1997 through May 1999. Incubations at the maximum and minimum temperatures, 24°C (August 1998) and 4°C (January 1999), represent most major seasonal differences and are contrasted in detail in Chapter 3. Start-up effects and seasonal patterns are explored in Chapter 4 using results for all incubations.

CHAPTER 2

MATERIALS AND METHODS

Experimental Approach and System Design

A greenhouse experiment was conducted in the Plant Growth Center at Montana State University in Bozeman, MT. Model subsurface wetlands were used to evaluate plant species influence on transformation of C, N, P, and S, and on the root-zone chemical environment. The experiment involved four plant treatments (*Carex rostrata, Scirpus acutus, Typha latifolia,* and unplanted control) and eight replicates arranged in a completely randomized design. A series of seventeen 20-day batch incubations of simulated wastewater were conducted at different temperatures and stages of plant growth to assess seasonal variability in plants influence on wastewater treatment. Incubation temperatures were 4°C in January and February 1998, increased in 4°C increments to a high of 24°C in August 1998, then decreased in 4°C increments reaching 4°C in January 1999, and increased again in 4°C increments reaching 16°C in May 1999. Relative humidity ranged from 30 to 70%, with no seasonal pattern. Supplemental lighting was not used; cumulative daily net solar radiation ranged from 1 to 8 MJ m^{-2} d^{-1} and was about 25% of locally recorded net solar radiation (Towler 1999). Seasonal variation of temperature and light was sufficient to reproduce seasonal cycles of plant dormancy and growth.

Thirty-two columns (8 replicates) were constructed from polyvinyl chloride (PVC) pipe (60 cm X 20 cm) and filled to a depth of 50 cm with washed pea gravel (1.5-2.0 cm diameter) (Figure 1). Porosity was 0.27 with a resulting pore volume of 4.3 L and did not differ significantly among treatments. Access tubes (1.1 cm inner diameter PVC pipe) for platinum redox electrodes and solution sampling tubes (0.3 cm inner diameter vinyl tubing) were installed vertically with openings at three depths: 5, 15, and 30 cm. A water delivery system was used to replace evaporative losses and continuously maintain water levels at the gravel surface by adding tap water to the bottom of the columns. Of these 32 columns, 16 (4 replicates) were routinely sampled to track C, N, P, and S transformations while the other 16 were treated in a like manner but not sampled. Redox potential was measured for all 32 columns.

Mature *Typha latifolia* (broadleaf cattail) and *Scirpus acutus* (hardstem bulrush) plants were collected in March 1997 near Norris, Montana and Three Forks, Montana, respectively. Plants were dormant when collected in early spring; no new growth was visible. Shoots were cut 15 cm above rhizomes, and plants were placed in cold (1°C), dark storage for one month. After cold storage, rhizomes were washed to remove sediment and planted in gravel-filled columns. Mature *Carex rostrata* (beaked sedge) plants were collected in April 1997 near Norris, Montana. Plants were collected early in the growing season; minimal new growth was visible. Shoots were cut 15 cm above rhizomes, which were washed free of sediment and planted directly in columns.