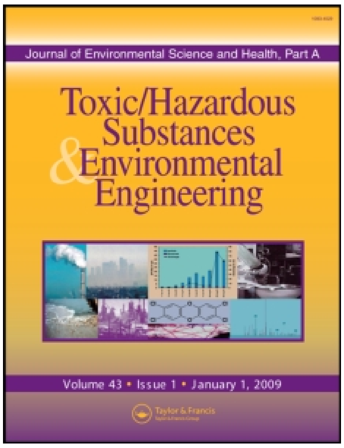

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Temperature, Plants, and Oxygen: How Does Season Affect Constructed Wetland Performance?

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The influence of temperature and plant-mediated oxygen transfer continues to draw attention from researchers, practitioners and regulators interested in the use of constructed wetlands for wastewater treatment. Because the vast majority of research on constructed wetland performance has been conducted during periods of active plant growth, the true influence of temperature, season, and plant species selection on constructed wetlands performance has not yet been evaluated adequately. In this article, we briefly summarize changes in the understanding of these influences on wetland performance, and suggest that effects of temperature and oxygen transfer are not readily separable because both factors respond to seasonal cycles and because effects of one can offset the other. We further speculate that the net effect of seasonal variation in these factors is such that plant-mediated oxygen transfer affects water treatment most in winter. Results of controlled-environment experiments conducted at Montana State University support these perspectives. Different plant species' capacities to oxidize the root zone responded differently to seasonal cycles of growth and dormancy, and species' effects on wastewater treatment were most pronounced in winter.

Key Words: Treatment wetland; Typha; Scirpus; Carex; Redox; Species; Cold climate; Winter.

INTRODUCTION

The effects of temperature, season, and plant-mediated oxygen transport on the performance of constructed wetlands (CWs) for wastewater treatment continue

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to be some of the more discussed and debated issues associated with this technology. Many early reports suggested that the carbon and nitrogen removal efficacy of constructed wetlands decreased sharply with decreased temperature, and some data support this supposition.[1–4] This reasoning was based on the well-documented fact that microbial growth rates and rates of treatment processes assayed in vitro decrease sharply with decreasing temperature. However, results of many other studies suggest that CW performance does not respond to temperature as expected. Reviewing available data, Kadlec and Knight[5] found there was little, if any, influence of temperature on organic carbon removal (as measured by COD, BOD or DOC tests), and Kadlec and Reddy[6] concluded that if any relation exists, it is negative. (i.e., performance decreases as temperature increases).

Similarly, early publications suggested that plants play a strong, positive role in CW performance.[1–3] Assuming aerobic metabolic pathways were responsible for observed organic carbon removal, several studies[7,8] estimated high rates of plant-mediated oxygen transport. However, further research indicated poor oxidation of reduced nitrogen compounds, evidence of the importance of alternative anaerobic metabolic pathways, and a largely anaerobic root zone.[5,9,10] Therefore, the early studies likely overestimated the oxygen transfer capabilities of wetland plants. Recent publications on CW design[5,11] have downplayed their importance to wastewater treatment, relegating the benefits of plants primarily to their ornamental, wildlife habitat, and thermal insulation value.

We believe that the physiological response of some plant species to seasonal dormancy and lower temperature permits increased oxygen transfer to the root zone of subsurface constructed wetlands, while the potential for plants to enhance aerobic treatment processes is more limited during periods of active plant growth and higher temperature. Assuming oxygen availability frequently limits the rates of microbial processes in wetlands, winter-elevated oxygen availability could offset the reduction of microbial activity due to cold temperatures. In this article we summarize research conducted with coworkers at Montana State University indicating that plant effects on root zone oxidation and wastewater treatment vary both seasonally and between species. Based on these studies, we argue that effects of plant species selection on CW performance is likely to be important in regions subject to extended periods of low temperatures and plant dormancy, and that plant selection should consider wastewater composition and treatment objectives.

RESEARCH RESULTS

We have conducted a series of greenhouse and laboratory studies of seasonal variation in model CW systems receiving various synthetic wastewaters simulating domestic and animal-derived wastewater,[12–15] metalliferous mineland runoff,[15,16] and solvent-contaminated laboratory or industrial effluent.[17] Procedural details can be found in the specified references, but within each study, influent concentrations of contaminants were uniform across seasons, reducing statistical “noise” compared to studies of operational CW systems with varying wastewater composition. This allowed controlled evaluation of seasonal variation related to temperature and plant growth. Each study compared several plant species across seasons, with conditions ranging from warm temperatures (typically 24°C), long days, and active plant growth to cold temperatures (typically 4°C), short days, and plant dormancy. Research focused on seasonal variation in contaminant removal and effects of plant species on cold-season CW performance rather than process-level analyses of oxygen transfer and microbial metabolism, but the apparent effects of plants on root zone oxidation status and redox-sensitive processes emerged as a common thread linking the studies.

Allen et al.[12] tracked chemical oxygen demand (COD) removal, redox potential (Eh), and sulfate concentration over 20-day periods in batch-loaded wetland microcosms (Fig. 1). No differences in any parameter were displayed between plant species when operated at 24°C (during active plant growth), but at 4°C (during plant dormancy) there were statistical differences in the COD removal time series among species, with removal decreasing in the order *Carex rostrata** > *Scirpus acutus* > *Typha latifolia* > unplanted controls. Only *Typha* and controls showed decreased removal at 4°C versus 24°C; *Carex* wetlands actually showed improved removal at 4°C. Eh and sulfate concentration were uniformly low for all species and controls at 24°C but increased after 3 to 9 days in planted treatments at 4°C, especially *Carex* and *Scirpus* wetlands. Sulfate and sulfide concentration were inversely related (not shown).

Hook et al.[13] compared COD removal, Eh, and sulfate concentration at day 6 of the 20-day batches across a year-long cycle in which temperature was varied from 24°C to 4°C and back to 24°C in 4°C steps (Fig. 2). Results corroborate and extend conclusions drawn by Allen et al.;[12] strong differences between species were apparent during cold temperatures and plant dormancy but were minimal at warmer temperatures when plants were actively growing. Unplanted control wetlands displayed a classic temperature dependency with poorer COD removal at colder temperatures. *Typha* wetlands followed a similar trend, but temperature effects were dampened. *Scirpus* and *Carex* wetlands displayed a minimal or even inverse relationship between COD removal and temperature. Eh and sulfate concentration were elevated during periods of plant dormancy in *Scirpus* and *Carex* wetlands but were low year-round in unplanted control and *Typha* wetlands. These results indicate that *Scripus acutus* and especially *Carex rostrata* are capable of increasing root-zone oxygenation during periods

*Recent taxonomic revisions reclassify most North American *Carex rostrata* as C. *utriculata* and *Scirpus acutus*, globally, as *Schoenoplectus acutus*. We retain the earlier names for consistency with our publications.

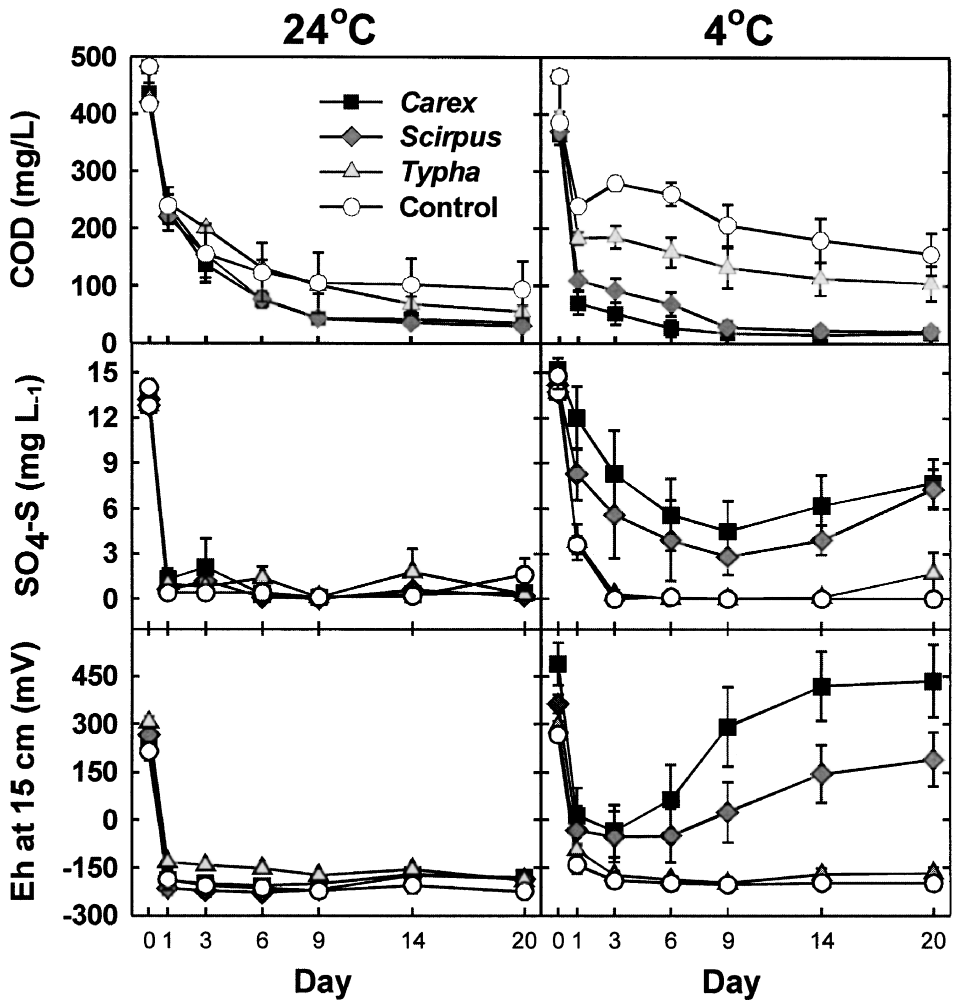

Figure 1: Time series of COD, sulfate concentration, and Eh during 20-day batch incubations at 24 and 4°C (Mean ± 1 SE). (Modified from Ref.12; used by permission of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.)

of plant dormancy at low temperatures, but not during active plant growth at high temperatures, and that this increase is sufficient to modify the overall chemistry of the wetland microcosm.

Riley et al.[14] concluded that seasonal effects on ammonium removal in batch-loaded *Carex* wetlands were influenced by both carbon load and temperature. Ammonium removal was diminished when initial COD (i.e., organic carbon) concentrations were high only in summer at 24°C; in winter at 4°C, ammonium removal was enhanced when influent COD load was increased. Therefore, warmer temperatures enhanced removal at low COD concentrations but reduced removal at high concentrations. We speculated that increased

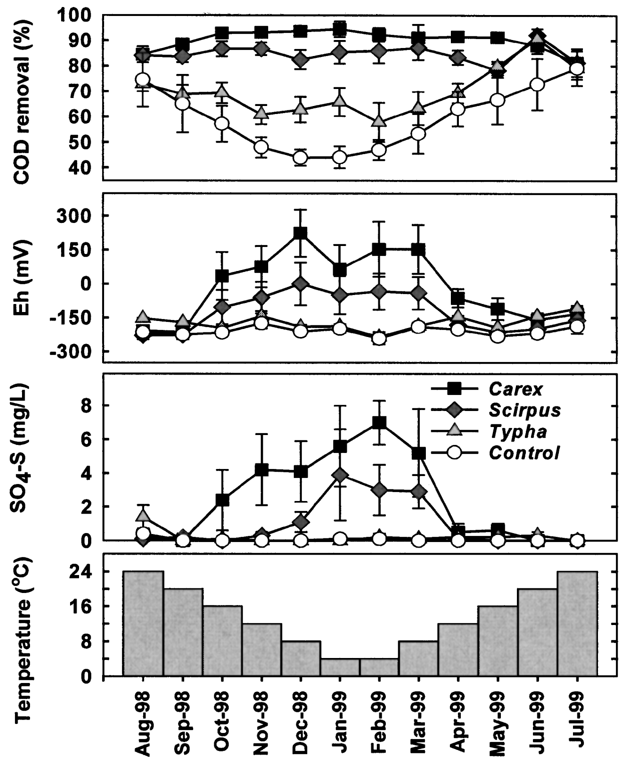

Figure 2: Seasonal variation of COD removal, Eh, and sulfate concentration at 15 cm depth in model constructed wetland microcosms on day 6 of 20-day batch incubations (mean ± 1 SE). Lower panel shows seasonal variation in greenhouse temperature. (Reproduced from Ref. 13; used by permission of WIT Press, Southampton, UK.)

oxygenation in winter, as observed previously in the same columns,[12,13] was sufficient to support both heterotrophic carbon oxidation and nitrification, while in summer competition for oxygen with heterotrophs limited nitrification. Nitrate levels were higher in winter, but not significantly, suggesting denitrification was occurring in all seasons.

Removal of most divalent metals from wastewater can occur through precipitation of metal sulfides. Sulfate reducing bacteria will utilize sulfate as an electron acceptor in the breakdown of organic carbon. Because the energy yield of this process is much lower than for aerobic breakdown of carbon, these microbes cannot compete with aerobic heterotrophs when oxygen is available and prefer anaerobic conditions.[18] Consequently, insufficient carbon, excess oxygen, or low temperatures may limit sulfate reduction, and metal-sulfide precipitation. Borden et al.[16] showed that sulfate reduction was limited by organic carbon availability at 24°C (during active plant growth) in *Scirpus*, *Typha*, and unplanted wetlands operated in either batch or continuous-flow mode. Sulfate reduction was only mildly inhibited at 4°C compared to 24°C in unplanted wetlands; however, cold temperatures inhibited sulfate reduction more in *Typha* wetlands and especially strongly in *Scirpus* wetlands. In *Scirpus* wetlands, this resulted in less effective zinc removal at 4°C than 24°C. Measured Eh were low for all treatments at 24°C, but were elevated for *Typha* and, especially, *Scirpus* wetlands at 4°C. In all seasons, virtually all available organic carbon was consumed (COD values approached zero), indicating similar conditions of carbon limitation of sulfate reduction. We concluded that increased inhibition of sulfate reduction in planted wetlands during winter was most likely due to increased competition with aerobic heterotrophs, due to increased oxygen availability as indicated by higher Eh values.

Kowles[17] simulated treatment of wastewater from an instructional laboratory building to evaluate a potential onsite greenhouse CW system. Batch incubation experiments compared five plant treatments (unplanted control, *Juncus effusus, Carex lurida, Pontederia cordata*, and *Iris pseudacorus*) and three nonhalogenated, polar, organic solvents (1-butanol, acetone, tetrahydrofuran) during summer (24/16°C day/night) and winter (13/7°C). Overall performance and differences between summer and winter performance depended strongly on presence and species of plants, with *Juncus effusus* providing the best overall performance and the least loss of performance during winter. Observed concentrations of sulfide, sulfate, and intermediate products of solvent degradation suggested that performance differences were partly due to differences in root zone oxygenation, while estimates of solvent loss via the plant transpiration stream suggested that this pathway also contributed to species and seasonal differences.

DISCUSSION

Three main conclusions may be drawn from our studies. First, seasonal variation in constructed wetland performance is modified strongly by presence (or absence) and species of plants and, due at least in part to these plant effects, temperature is poor predictor of seasonal performance. Second, effects of plants on seasonal performance patterns appear to be explained largely by seasonal variation in root-zone oxidation, although seasonal patterns of other plant-mediated processes such as nutrient uptake, plant biomass production and detritus production probably also play a role. Third, the effects of plants on performance are frequently greatest during the coldest periods, during dormancy, implying that plant species selection may be more important to cold-season than to warm-season performance.

Our results indicate that temperature is at best a secondary predictor of constructed wetland performance. Depending on the wastewater composition and the presence and species of plants, contaminant removal may be less effective, equally effective, or more effective in winter than summer. With plants present, dissolved metal removal via microbial sulfate reduction and metal-sulfide precipitation was less effective in winter, apparently due to more oxidized conditions. Overall COD removal in unplanted controls and *Typha* wetlands also was positively correlated to temperature but there was no, or even a negative, correlation between COD removal and temperature in *Scirpus* and *Carex* wetlands. Solvent removal was positively correlated to temperature for all plant treatments, but much of the increased warm temperature removal was attributed to increased transpiration losses during active plant growth, not temperature, and wintertime reductions in performance were much greater with some species than others. The temperature influence on ammonium removal in *Carex* wetlands was strongly influenced by the initial COD concentration; there was a positive correlation with temperature at low COD concentrations but a negative one at high concentrations.

Across all of our studies, plant-mediated seasonal variation in redox conditions appears to be a better predictor of seasonal performance variation than temperature. Correlations between Eh and contaminant removal were measured directly in most of our studies,[12,13,16] and can be inferred from redox-dependent processes such as the sulfate-sulfide couple in the others.[14,17] When Eh (or surrogate variables such as sulfate concentrations) were higher, removal mechanisms enhanced by aerobic microbial processes, such as COD removal and nitrification, were greater and removal mechanisms enhanced by anaerobic microbial processes, such as denitrification and metal sulfide precipitation, were diminished. It appears that during warm temperatures and active plant growth, anaerobic pathways were the primary removal mechanism for all treatment processes regardless of presence or species of plant. During these periods, measured Eh was well below 0 mV, and usually below –150 mV (dissolved oxygen never exceeded 1.0 mg/L at any time in any study). In contrast, all data suggest that aerobic treatment processes were enhanced in planted treatments during cold temperatures and plant dormancy. This wintertime enhancement of oxidation appears to be species dependent: minimal in *Typha latifolia*, much greater in *Scirpus acutus* and best in *Carex rostrata*, among the species used in most of our studies. A direct negative effect of decreased temperature was expressed only in cases where a seasonal shift in the balance of aerobic and anaerobic metabolism could not be inferred (e.g., COD removal in unplanted controls and *Typha* wetlands) or where physical processes not dependent on redox conditions appeared to be important (e.g., organic solvent removal).

The ability of wetland plants to transport oxygen to root tissue and the associated leakage of oxygen into the root zone is well documented.[19,20] The magnitude of both processes is generally accepted to be species dependent, but there is little information on seasonal variation in oxygen transfer. Seasonal variation is expected to result from variation in internal oxygen transport and root respiration due to seasonal cycles of temperature, light, photosynthesis, stomatal activity, and internal storage and consumption of carbon and nutrients. Early constructed wetland design manuals[1,4] assumed oxygen transfer to the root zone would be greater during periods of active plant growth. However, the quantity of oxygen available for processes external to the root is vigorously debated.[21–25] Because root and microbial respiration must compete for limited oxygen in wetlands,[26,27] seasonal variation in root metabolism would be expected to affect root-zone oxidation status even if oxygen transport from shoots to roots were constant. Reduced internal oxygen consumption due to cold temperatures and dormancy appears to allow greater oxygen leakage from roots of some plant species during the cold season or in response to short-term temperature decreases.[22,27–29]

Could seasonal variation in oxygen transfer to the root zone induce a large enough shift in microbial metabolic pathways to significantly affect organic carbon degradation and other CW treatment processes? We have argued that anaerobic microbial metabolism is generally favored during active plant growth at warm temperatures, when most oxygen is consumed within the root. In contrast, aerobic microbial respiration is sometimes favored during dormancy at cold temperatures, when root respiration is lower and more oxygen is available to microbes in the root zone. The efficiency of aerobic respiration over anaerobic respiration is so great that only a modest shift toward aerobic conditions could obscure or even reverse the effect of temperature on microbial activity.[18]

As a crude illustration of this effect, assume removal of COD by aerobic and anerobic respiration pathways can be modeled by a first order reaction equation and that the Van Hoft-Arrhenius relation adequately describes the effect of temperature. Further assume standard BOD test values $k_{20} = 0.23\ d^{-1}$ and $\theta = 1.047$ are applicable for aerobic respiration and that anaerobic respiration proceeds at one tenth the rate of aerobic respiration but with the same temperature effect ($k_{20} = 0.023\ d^{-1}$; $\theta = 1.047$). Figure 3 shows total COD removal

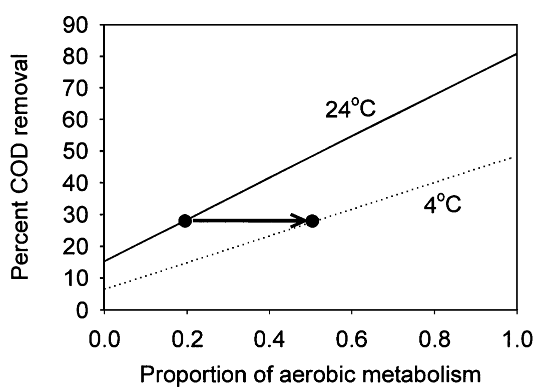

Figure 3: Illustration of the combined effects of temperature and proportion of aerobic versus anaerobic metabolism involved in COD degradation, as estimated using a standard first-order kinetic model. The two points connected by the arrow are one example of how an increase in the proportion of aerobic metabolism, by about 30% in this case, can potentially allow equivalent contaminant removal in spite of a temperature reduction from 24 to 4°C.

at day 6 as a function of the fraction of removal that is due to aerobic respiration F_a, and assuming anaerobic respiration was occurring simultaneously and responsible for the remaining quantity $(1-F_a)$ of COD removal. With these rough but reasonable estimates, it is clear that the influence of the type of respiration at either 4°C or 24°C is greater than the effect of temperature for a given proportion of aerobic metabolism. Equal COD removal is possible at 4°C and 24°C if the proportion of aerobic respiration is 20–50% higher at the lower temperature. Thus, moderate increases in oxygen availability in winter could offset effects of cold temperatures. Other explanations including variable loading rates and carryover of organic matter between seasons may also apply and are not mutually exclusive.[5,6]

Our studies also suggest that the total oxygen demand of wastewater modifies the effects of plants on seasonal redox conditions and oxidative treatment processes. During batch incubations in winter, Eh did not increase until after COD levels were reduced below 100 mg/L.[12] Lower levels of COD increased ammonium removal only during summer, when evidence indicated that oxygen availability was lower; higher levels of COD increased ammonium removal in winter when oxygen was more available.[14] Solvent removal was also more rapid and complete with lower initial COD concentrations.[17] Inferences about plant-mediated oxygen transport in natural wetlands not influenced by anthropomorphic carbon loading may not transfer directly to constructed wetlands subject to high carbon loading.[24,30] At higher levels of external demand, oxygen release rates are limited by root surface area and tissue characteristics and cannot meet demand.[30] Considering the combined effects of internal root respiration, external oxygen demand, and structural constraints on diffusion, the potential for elevated Eh and aerobic microbial metabolism is greatest when temperatures are cold, plants are dormant, and COD levels are low.

In addition to the effects of COD loading, our studies show that the practical consequences of seasonal and plant-species effects depend on wastewater composition and treatment objectives. Plant species and climatic conditions that favor oxidative processes may promote removal of some contaminants but inhibit removal of others. For example, the presence of *Carex rostrata* or *Scirpus acutus* promoted COD removal, particularly at low temperatures,[12,13] but the combination of *Scirpus acutus* and low temperatures inhibited removal of zinc by sulfate reduction and zinc-sulfide precipitation;[16] both results appeared to reflect enhanced oxygen availability at low temperatures.

There is little research comparing the relative performance of different plant species in cold-region subsurface wetlands. Most research involves just a few species, and direct comparisons between species have focused mostly on growing season performance at relatively warm temperatures. However, our results suggest that the overall influence of plants and differences between species might be greater during periods of low temperature and plant dormancy. As a result, the choice of plants is potentially more important to subsurface wetland performance during the winter than during the growing season.

The plant effects described here may be more pronounced in batch-loaded than continuous-flow CW systems. Stein et al.[15] hypothesized that batch hydraulic loading ensures that the entire microbial population will be exposed episodically to decreasing organic carbon concentrations. This decrease in oxygen demand in turn can allow root-zone Eh to increase over the course of a batch incubation, particularly when plants are dormant and oxygen transfer rates apparently are higher. Temporal variation in oxygen supply and Eh may select for more robust, aerobically facultative biofilms capable of rapid sequestration of COD and nutrients for utilization later in the batch cycle.

CONCLUSIONS

Based on results of our studies and information available from others, we believe that plant-mediated oxygen transport to the rhizosphere varies among species and seasons, and that the interactions between plants and seasonal variations in temperature and other factors can strongly influence contaminant removal processes in CWs. In the presence of some plants, but not others, these interactions tend to shift microbial metabolic pathways from predominantly anaerobic during warm periods with active plant growth towards an increased contribution by aerobic respiration and other oxygen-dependent processes during cold periods and plant dormancy. However, it is likely that overall organic carbon load and mode of hydraulic operation influence this potential shift; high carbon loading and continuous-flow operation likely dampen seasonal and plant effects by maintaining continuously high oxygen demand in the root-zone and limiting development of oxidizing conditions. Practical consequences of differences in root-zone oxidation will depend on wastewater type and the importance of oxidative and reducing processes to treatment. Better understanding of seasonal variation in processes responsible for CW performance should lead to improved design and management of these systems, making them viable technologies for wastewater treatment in cold temperate climates. To achieve this understanding, it is critical to recognize that seasonality comprises much more than temperature.

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REFERENCES

1. United States Environmental Protection Agency. *Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment*, EPA/625/1-88/002. Center for Environmental Research Information: Cincinnati, OH, USA, 1988.

2. Water Pollution Control Federation. *Natural Systems for Wastewater Treatment, Manual of Practice FD-16*; Task Force on Natural Systems, S.C. Reed, Chair. Water Pollution Control Federation: Alexandria, VA, USA, 1989.

3. Reed, S.C. *Subsurface Flow Constructed Wetlands for Wastewater Treatment: a Technology Assessment*, Rep. 832-R-93-001; U.S. Environmental Protection Agency, Office of Water: Washington, DC, USA, 1993.

4. Reed, S.C.; Crites, R.W.; Middlebrooks, J.E. *Natural Systems for Waste Management and Treatment*; McGraw-Hill: New York, 1995.

5. Kadlec, R.H.; Knight, R.L. *Treatment wetlands*: Lewis Publishers: Boca Raton, FL, 1996.

6. Kadlec, R.H.; Reddy, K.R. Temperature effects in treatment wetlands. Wat. Environ. Res. **2001**, *73*, 543–557.

7. Watson, J.T.; Reed, S.C.; Kadlec, R.H.; Knight, R.L.; Whitehouse, A.E. Performance expectations and loading rates for constructed wetlands. In *Constructed wetlands for wastewater treatment: Municipal, industrial and agricultural*. Lewis Publishers: Chelsea MI, 1989; 319–351.

8. Reddy, K.R.; D'Angelo, E.M.; DeBusk, T.A. Oxygen transport through aquatic macrophytes: The role in wastewater treatment. j. Environ. Qual. **1989**, *19*, 261–267.

9. Brix, H. Do macrophytes play a role in constructed treatment wetlands? Wat. Sci. and Tech. **1997**, *35* (5), 11–17.

10. Fortin, D.; Goulet, R.; Roy, M. Seasonal cycling of Fe and S in a constructed wetland: The role of sulfate reducing bacteria. Geomicrobiology J. **2000**, *17*, 221–235.

11. United States Environmental Protection Agency. *Manual: Constructed Wetlands Treatment of Municipal Wastewaters*, EPA/625/R-99/010; U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Office of Research and Development: Cincinnati, OH, USA, 2000.

12. Allen, W.C.; Hook, P.B.; Biederman, J.A.; Stein, O.R. Temperature and wetland plant species effects on wastewater treatment and root zone oxidation. J. Environ. Qual. **2002**, *31*, 1010–1016.

13. Hook, P.B.; Stein, O.R.; Allen, W.C.; Biederman, J.A. Plant species effects on seasonal performance patterns in model subsurface wetlands. In *Constructed wetlands for wastewater treatment in cold climates*; Mander, Ü; Jenssen, P.D., Eds., Advances in Ecological Sciences Vol. 11; WIT Press: Southhampton, UK, 2003; 87–106.

14. Riley, K.A.; Stein, O.R.; Hook, P.B. Ammonium removal in constructed wetland microcosms as influenced by the presence and species of plants, season, and organic carbon load. J. Environ. Sci. and Health Pt A. **2005**; *40*, (6–7), xx–xx.

15. Stein, O.R.; Hook, P.B.; Biederman, J.A.; Allen, W.C.; Borden, D.J. Does batch operation enhance oxidation in subsurface constructed wetlands? Wat. Sci. Tech. **2003**, *48*(5), 149–156.

16. Borden, D.J.; Stein, O.R.; Hook, P.B. Seasonal effects of supplemental organic carbon on sulfate reduction and zinc sulfide precipitation in constructed wetland microcosms. In *Proceedings, International Ecological Engineering Society Meetings*, Nov. 26–29, 2001, Lincoln University, New Zealand, 2001; 296–300.

17. Kowles, J.L. *The Fates of Three Polar Organic Solvents in a Microcosm Constructed Wetland Wastewater Treatment System*, M.Sc. Thesis. Montana State University, Bozeman, MT, USA, 2001.

18. Fenchel, T.; Finlay, B.J. *Ecology and evolution in anoxic worlds*. Oxford University Press: Oxford, UK, 1995.

19. Armstrong, W.; Armstrong, J.; Beckett, P.M. Measurement and modeling of oxygen release from roots of phragmites australis. In *Constructed wetlands in water pollution control*; Cooper, P.F., Findlater, B.C., Eds. Pergamon Press: Oxford, UK, 1990; 41–51.

20. Bedford, B.L.; Bouldin, D.R.; Beliveau, B.D. Net oxygen and carbon dioxide balances in solutions bathing roots of wetland plants. J. Ecol. **1991**, *79*, 943–959.

21. Gries, C.; Kappen, L.; Losch, R. Mechanism of flood tolerance in reed, phragmites australis (Cav.) Trin. ex Steudel. New Phytologist **1990**, *114*, 589–593.

22. Howes, B.L.; Teal, J.M. Oxygen loss from spartina alterniflora and its relationship to salt marsh oxygen balance. Oecologia **1994**, *97*, 431–438.

23. Steinberg, S.L.; Coonrod, H.S. Oxidation of the root zone by aquatic plants growing in gravel-nutrient solution culture. J. Environ. Qual. **1994**, *23*, 907–913.

24. Sorrell, B.K.; Armstrong, W. On the difficulties of measuring oxygen release by root systems of wetland plants. J. Ecol. **1994**, *82*, 177–183.

25. Bedford, B.L.; Bouldin, D.R. Discussion of on the difficulties of measuring oxygen release by root systems of wetland plants by B.K. Sorrell; W. Armstrong, J. Ecol. **1994**, *82*, 185–186.

26. Jackson, M.B.; Armstrong, W. Formation of aerenchyma and the process of plant ventilation in relation to soil flooding and submergence. Plant Biology **1999**, *1*, 274–287.

27. Moog, P.R.; Brüggemann, W. Flooding tolerance of Carex species. II. Root gas-exchange capacity. Planta **1998**, *207*, 199–206.

28. Crawford, R.M.N. Oxygen availability as an ecological limit to plant distribution. advances. Ecological Res **1992**, *23*, 93–185.

29. Callaway, R.M.; King, L. Temperature-driven variation in substrate oxygenation and the balance of competition and facilitation. Ecology **1996**, *77*, 1189–1195.

30. Sorrell, B.K. Effect of external oxygen demand on radial oxygen loss by juncus roots in titanium citrate solutions. Plant, Cell, and Environment **1999**, *22*, 1587–1593.

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