TREATMENT OF DOMESTIC WASTEWATER BY THREE PLANT SPECIES IN CONSTRUCTED WETLANDS

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Abstract. Three common Appalachian plant species (*Juncus effusus* L., *Scirpus validus* L., and *Typha latifolia* L.) were planted into small-scale constructed wetlands receiving primary treated wastewater. The experimental design included two wetland gravel depths (45 and 60 cm) and five planting treatments (each species in monoculture, an equal mixture of the three species, and controls without vegetation), with two replicates per depth × planting combination. Inflow rates (19 L day^{-1}) and frequency (3 times day^{-1}) were designed to simulate full-scale constructed wetlands as currently used for domestic wastewater treatment in West Virginia. Influent wastewater and the effluent from each wetland were sampled monthly for ten physical, chemical and biological parameters, and plant demographic measurements were made. After passing through these trough wetlands, the average of all treatments showed a 70% reduction in total suspended solids (TSS) and biochemical oxygen demand (BOD), 50 to 60% reduction in nitrogen (TKN), ammonia and phosphate, and a reduction of fecal coliforms by three orders of magnitude. Depth of gravel (45 or 60 cm) had little effect on wetland treatment ability, but did influence *Typha* and *Scirpus* growth patterns. Gravel alone provided significant wastewater treatment, but vegetation further improved many treatment efficiencies. *Typha* significantly out-performed *Juncus* and *Scirpus* both in growth and in effluent quality improvement. There was also some evidence that the species mixture out-performed species monocultures. *Typha* was the superior competitor in mixtures, but a decline in *Typha* growth with distance from the influent pipe suggested that nutrients became limiting or toxicities may have developed.

Keywords: constructed wetlands, domestic wastewater treatment, *Juncus effusus*, *Scirpus validus*, *Typha latifolia*

1. Introduction

Many Appalachian households and rural communities lack centralized wastewater collection and treatment facilities due to mountainous topography, low population densities or a lack of financial resources. Typically, on-site treatment consists of a septic tank to settle solids, followed by a soil drain field. However, soil drain fields may fail in steep rocky terrain or where groundwater or impervious rock layers lie close to the surface. Unacceptable health and aesthetic problems are associated with untreated sewage pooling on the ground surface, or being directly discharged into receiving waterways.

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Constructed wetlands of many kinds are receiving much attention where alternatives to failing septic tank-soil drain field systems are needed. The wetlands provide a low-cost, easily-managed system that can treat water to acceptable levels for discharge waterways (USEPA, 1977). Good aesthetic properties and effective treatment capabilities make subsurface flow wetlands an appropriate choice for small-scale, individual or small group residential situations (Hiley, 1995; Knight, 1993; Knight *et al*., 1993; Steiner and Combs, 1993). In these systems wastewater from the septic tank enters a few inches below the substrate surface, and the water level is maintained by the outflow. The subsurface flow avoids mosquito breeding conditions, reduces objectionable odors, and decreases the possibility of human or animal contact with untreated wastewater. Appropriate plantings can hide the functional nature of the wetland, which can be an attractive addition to the home landscape with minimal care.

Small-scale constructed wetlands for rural domestic wastewater treatment are a relatively new technology, and the physical, chemical and biological processes which facilitate treatment are still poorly understood. Several recent volumes have been published discussing the progress being made in our understanding of how these systems function (e.g., Hammer, 1989; Kadlec and Knight, 1995; Moshiri, 1993; Reddy and Smith, 1987; Reed *et al*., 1995; USEPA, 1988). The inconsistent treatment results suggest that further research is needed to optimize system functioning. In particular, knowledge of the roles played by plants in these treatment systems is still lacking, and little research has compared different plant species or species mixtures in promoting treatment.

Plants facilitate microbial activity in both natural and constructed wetlands by providing attachment sites, carbon and oxygen in the rhizosphere (Armstrong, 1964; Brix, 1994, 1997). In subsurface flow wetlands, the limited contact of the wastewater with the atmosphere coupled with the high biological oxygen demand (BOD) of the influent wastewater stream results in anaerobic conditions predominating throughout the water column. While plant roots are usually ineffective in bulk oxygenation of the wastewater stream, local oxidized environments on or near root surfaces can harbor aerobic microbes which are thought to promote many treatment processes. Anaerobic conditions slow or prevent some processes of waste degradation such as nitrification (Steinberg and Coonrod, 1994; Tanner *et al*., 1995) and the oxidation of organic solids (lowering of BOD) (Brix, 1994). Anaerobic fermentation can also produce toxic substances such as hydrogen sulfide and volatile fatty acids (Wetzel, 1993). Roots may also increase microbial activity through the production of organic carbon and the release of substances such as sugars and amino acid exudates. Plants in constructed wetlands also serve to stabilize the bed surface, increase porosity throughout the wetland volume, insulate the bed against freezing through litter production, absorb and store plant nutrients, prevent channelized flow, and improve wetland aesthetics (Tanner and Sukias, 1995).

Further research on many design parameters is needed to optimize the treatment abilities of these systems (e.g., Reed and Brom, 1992; Crites, 1994). For example, while numerous plant species have been included in various wetlands plantings, few studies give comparative data upon which to evaluate the relative effectiveness of different plant species in improving effluent quality (Gersberg *et al*., 1984), and no studies have evaluated whether species mixtures may be superior to monocultures. Further, the survival and growth responses of the individual plant species themselves have not been researched in the context of the conditions found in subsurface flow constructed wetlands.

The objectives of this study were to determine the effects of different plant species on wastewater treatment by small-scale wetlands. Our treatments included wetland substrate depth and five vegetation types. We hypothesized that the three common Appalachian plant species we selected for investigation would differ in their treatment abilities, but that they would provide superior treatment to troughs lacking vegetation. We also hypothesized that a species mixture would prove superior to any component species in monoculture. These hypotheses are derived from our expectations that plant roots facilitate wastewater treatment processes, and that partitioning of the rooting zone among multiple species will maximize root biomass in the wetland substrate, resulting in more efficient wastewater treatment.

2. Methods and Materials

The research was conducted at the Morgantown, WV, municipal wastewater treatment facility. Twenty 400-L black plastic cattle troughs (1.5 × 1 m oval) were filled with pea gravel to either 45 cm ('shallow') or 60 cm ('deep'). Each trough received one of five planting treatments: no plants, monocultures (15 plants/trough) of *Juncus effusus*, *Scirpus cyperinus*, or *Typha latifolia*, or equal numbers (5 plants/species/trough) of the three species ('mixture'). There were two replicate troughs of each planting by depth treatment.

The troughs were initially filled with gravel in the fall of 1993 and filled with tapwater. Plants were transplanted from farm ponds in April and May of 1994. Wastewater was introduced in June 1994 and data collection began in July, 1994. Unexpected plant mortality in many troughs during the winter of 1994–1995 required the replacement of many plants in April, 1995, when spring regrowth began. Troughs were weeded as necessary to eliminate 'volunteer' species.

Each trough received 19 L of primary treated wastewater per day, in three equal applications (8 am, 12 noon, and 6 pm). Retention time was estimated at about 6 days for the 'shallow' troughs and 8 days for the 'deep' troughs, although it probably lessened as plant root growth, silt accumulation and biofilm formation filled voids between the gravel (Kadlec and Watson, 1993; Taylor *et al*., 1990). These flow rates, frequencies and retention times were selected to approximate those of household wastewater streams into full-scale individual residential constructed wetlands (Crites, 1994).

Ten physical, chemical and biological measurements were made monthly on the influent and on the effluent from each of the troughs from July, 1994, through July, 1995. Influent and effluent samples from each trough were collected in sterile 1-L Nalgene bottles. Approximately 200 mL of sample were used to measure electrical conductivity, pH, dissolved oxygen (DO), and total dissolved solids (TDS) at the time of collection using a YSI Model 3500 Meter (Yellow Springs Instruments, Yellow Springs, OH) equipped with appropriate probes following standard methods (APHA, 1992). Another 15 mL of sample were filtered through 0.45 μm filters (Millipore Corp., Bedford, MA), acidified to pH < 2.0 with concentrated hydrochloric acid, placed into 15 mL sterile polypropylene centrifuge tubes (Corning), and stored at –20 °C until processing for phosphorus by flame emission spectroscopy using ICP-AES (Perkin Elmer model 400). The remaining portions of sample were stored on ice for transport to the laboratory, where they were immediately transferred to a refrigerator for storage at 4 °C until processing.

Samples were analyzed for total suspended solids (TSS) and biological oxygen demand (BOD) following standard methods (APHA, 1992). Total Kjeldahl nitrogen (TKN) and ammonia were determined by the Kjeldahl method (Bremmer and Mulvaney, 1982). Modifications for ammonia determination involved the use of calcium carbonate as the alkaline solution and elimination of the digestion step.

Fecal coliform densities were determined by the membrane filtration technique (APHA, 1992) using Millipore type HA 0.45-μm pore-size membrane filters and enumerated on M-FC medium. Three volumes were tested for all samples to increase the probability of obtaining plate counts within acceptable ranges. Plates were enclosed in a plastic bag containing moist towels to prevent desiccation and incubated at 44.5 °C for 24 hr. After incubation, fecal coliform colonies were counted.

The wastewater data were analyzed using a repeated measures analysis of variance (JMP, 1994). Multiple comparison tests (‘contrasts’) were performed between (1) influent vs. no plants (effect of gravel alone), (2) no plants vs. all planted troughs (effect of vegetation), (3) mixture vs. monocultures (effect of species’ niche differentiation on overall treatment), and (4) mixture vs. *Typha* monoculture (effect of *Typha* as a component of the species mixture). As gravel depth was not found to have a significant influence on most treatment efficiency parameters, deep and shallow troughs were pooled within each vegetation treatment.

Demographic measurements were made on all individual transplants, following the techniques of demographic growth analysis suggested by McGraw and Garbutt (1990). No harvests of above-ground material were undertaken (to simulate no maintenance of the wetland by a homeowner), and no direct root growth measurements were obtainable. Plants were censused in July, 1994 (after establishment), September/October, 1994 (end of first year), and again in September, 1995 (end of second year). In 1994, *Scirpus* and *Juncus* tillers (both vegetative and flowering) were counted and relative growth rates were calculated as the natural log of the difference between initial and final tiller numbers. For *Typha*, we were unable to assign new shoots to specific ‘mother’ plants (as was possible with *Juncus* and *Scirpus* in 1994), hence it was not possible to obtain relative growth rates based on a transplanted individual’s total leaf production. Therefore leaf production was censused only for the transplanted shoots, the longest leaf length from each was measured, and new shoots were counted on a whole-trough basis. The census of all plants (all species) at the end of the second summer (1995) was also done on a whole-trough basis for the same reason. However, due to the replanting necessitated by the winter mortality, tiller numbers (1994) were not compared to 1995 numbers. To account for the differences in initial planting numbers of each species (5 per species in mixture troughs, 15 per species in monoculture troughs), totals for each species’ shoot or tiller production in mixture were multiplied by three before analysis. The data were analyzed by ANOVA (JMP, 1994) for each species to compare: (1) growth in deep troughs vs. growth in shallow troughs, and (2) growth in monoculture vs. growth in mixture.

3. Results and Discussion

3.1. Wastewater treatment

The least square means and the results of the contrasts for the chemical and biological treatment parameters are shown in Table I. The means are generally within the broad ranges reported in the literature for similar systems (e.g., USEPA, 1988; Hiley, 1995; Knight *et al.*, 1993; Steiner and Combs, 1993). When effluent water of all treatments was averaged and compared to influent wastewater, reductions of between 50 to 70% in TSS, BOD, TKN, ammonia, phosphate and fecal coliforms were realized. Depth of gravel (contrast of deep vs. shallow troughs) had little effect on most treatment parameters, although it showed some influences on plant growth (Table II). Unvegetated troughs significantly influenced many treatment parameters as did the presence of vegetation over and above that of gravel alone. The three species clearly differed in their overall influence, and there were some indications that species mixtures may outperform species in monoculture.

The effluent data provided no direct evidence to recommend deeper systems over shallower ones, despite the greater retention times expected in deeper troughs. Increased evapotranspiration (relative to total liquid volume) from the shallow troughs may account for the slightly higher levels of conductivity and TDS found in the shallow gravel troughs, but no measurements of total effluent volume from the troughs were made.

One partial explanation for the lack of differential effects of the two depth treatments may lie in the root morphologies of the species used-*Typha* is thought to be a somewhat shallower-rooting species than are *Juncus* or *Scirpus* (Gersberg *et al.*, 1984, although their *Typha* plants were evidently stressed and may not have reached maximal rooting depth). In this study, *Typha* generally facilitated treatment

TABLE I

Influent and effluent measurements of pH, conductivity, total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), biological oxygen demand (BOD), total Kjeldahl nitrogen (TKN), Ammonia, total phosphate, and fecal coliform. Values are means and standard errors of four troughs per treatment, deep and shallow replicates pooled

Treatment	pH	Conductivity	TDS	TSS	DO	BOD	TKN	Ammonia	Fecal phosphate	Coliform
	(units)	(mS cm^{-1})	(g L^{-1})	(mg L^{-1})						log(Cfu 100 mL^{-1})
Influent	7.13±0.09	0.72±0.12	0.36±0.06	74.5±4.8	1.23±0.36	137.2±12.4	14.7±2.0	12.2±1.8	1.28±0.22	8.21±0.48
No plants	7.13±0.05	0.68±0.06	0.34±0.03	12.3±2.4	1.69±0.18	42.5±6.4	10.5±1.0	8.5±0.9	0.76±0.11	5.73±0.26
Juncus	6.89±0.07	0.79±0.09	0.39±0.04	16.7±3.5	2.22±0.26	48.2±9.1	7.7±1.5	6.1±1.3	0.47±0.16	5.30±0.35
Scirpus	6.90±0.05	0.86±0.07	0.43±0.04	15.7±2.9	1.58±0.21	41.3±7.4	11.0±1.2	9.1±1.0	0.66±0.13	5.86±0.26
Typha	6.80±0.05	0.86±0.06	0.43±0.03	18.3±2.4	2.56±0.18	33.0±6.3	5.6±1.0	4.7±0.9	0.24±0.11	4.69±0.22
Mixture	6.70±0.05	0.97±0.06	0.49±0.03	19.9±2.6	2.72±0.19	35.5±6.6	3.8±1.1	3.2±0.9	0.19±0.12	4.68±0.26
Contrasts:										
Deep vs. shallow	n.s.	$p < 0.001$	$p < 0.001$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Influent vs. no plants	n.s.	n.s.	n.s.	$p < 0.001$	n.s.	$p < 0.001$	$p < 0.10$	$p < 0.10$	$p < 0.05$	$p < 0.001$
Plants vs. no plants	$p < 0.001$	$p < 0.01$	$p < 0.10$	$p < 0.10$	$p < 0.01$	n.s.	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.05$
Monocultures vs. mixture	$p < 0.01$	$p < 0.10$	$p < 0.10$	n.s.	$p < 0.01$	n.s.	$p < 0.01$	$p < 0.01$	$p < 0.05$	$p < 0.10$
Typha vs. mixture	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

TABLE II

Means and standard errors of demographic growth measurements of *Juncus effusus*, *Scirpus validus*, and *Typha latifolia* grown in deep (60 cm) and shallow (45 cm) troughs, in monoculture or in an equal mixture of the three species

		Mixture		Monoculture		Contrast of	Contrast of
		deep	shallow	deep	shallow	mixture vs. monoculture	deep vs. shallow
A.	*Juncus*, relative growth rate, 1994	1.12±0.112	1.04±0.064	1.32±0.112	1.25±0.064	$p < 0.05$	n.s.
B.	*Scirpus*, relative growth rate, 1994	0.48±0.085	0.47±0.085	0.73±0.049	0.54±0.049	$p < 0.05$	n.s.
C.	*Typha*, mean new leaves produced per established plant, 1994	3.20±1.0	3.00±1.1	1.90±0.6	0.70±0.6	$p < 0.05$	n.s.
D.	*Typha*, new shoots per established plant, 1994	2.10±0.19	1.70±0.19	1.60±0.19	1.50±0.19	$p < 0.10$	n.s.
E.	*Typha*, mean height of longest leaf (cm) per plant, 1994	181.10±6.11	175.90±6.44	177.30±3.72	161.10±3.72	$p < 0.10$	$p < 0.05$
F.	*Juncus*, tillers per trough, adjusted for initial planting densities, 1995	273.00±36.4	132.00±36.4	326.00±36.4	363.00±36.4	$p < 0.05$	n.s.
G.	*Scirpus*, tillers per trough, adjusted for initial planting densities, 1995	471.00±126	327.00±126	487.00±126	297.00±126	n.s.	n.s.
H.	*Scirpus*, mean number of tillers per plant, 1995	8.90±0.70	9.20±0.83	8.60±0.40	11.70±0.59	$p < 0.10$	$p < 0.01$
I.	*Scirpus*, flowering tillers per trough, 1995	27.50±2.78	7.50±2.78	52.50±2.78	11.50±2.78	$p < 0.01$	$p < 0.001$
J.	*Typha*, mean total leaves per shoot, 1995	6.05±0.44	7.82±0.37	6.98±0.26	6.88±0.29	n.s.	$p < 0.05$
K.	*Typha*, mean height of longest leaf (cm) per plant, 1995	103.90±4.16	99.30±3.98	135.30±2.80	104.20±3.30	$p < 0.001$	$p < 0.001$

better than did the other two species. If treatment were restricted to the middle and upper portions of the gravel where the *Typha* root biomass was greatest, no effect of depth would be predicted. Further, even for species with the potential for significant root growth at greater depth, maximal root biomass may not be achieved until subsequent growing seasons. Finally, our influent pipes were located just beneath the gravel surface of each wetland, and the effluent pipes were located about 10 cm above the bottom of the substrate (35 cm for shallow and 50 cm for deep). Therefore, some proportion of the deeper volume of each trough may have been outside the most direct line of water flow. Such channelized flow can significantly reduce the effective retention times of wetland systems. Thus the hypothesized advantages of greater depth (e.g., greater system volume without an increase in wetland surface area, increased retention time, increased surface area of the gravel, and greater total root surface area available to support aerobic microbes) were not demonstrated here, and may only be realized with different construction designs, planting regimes, or in later years of the wetland's lifespan.

Gravel alone (contrasts of influent vs. effluent from unvegetated troughs) improved six out of 10 water quality parameters. Simple retention in an unfavorable environment may explain much of the reduction in fecal coliform numbers. The ability of gravel alone to improve effluent quality might also be related to physical settling of suspended solids (Gersberg *et al*., 1984) or the formation of a 'biofilm' on the surface of the gravel. It is not known, however, whether biofilm formation would eventually reach an equilibrium, absorbing as much as releasing, with subsequent treatment provided only by the direct and indirect influences of plant roots. Such an equilibrium might also affect the long-term ability of binding sites on the gravel to adsorbions.

In most cases, effluent quality was further improved by the presence of vegetation (contrasts of all vegetated troughs vs. unvegetated troughs). The improvements in effluent quality are probably due both to direct nutrient uptake by the plants for growth, and to the actions of aerobic microbes harbored in the rhizosphere. While the transport of oxygen to the rhizosphere has been documented for a number of plant species (Armstrong, 1967a, b; Flessa and Fischer, 1992; Good and Patrick, 1987; Grosse *et al*., 1991; Jaynes and Carpenter, 1986; Moore *et al*., 1994; Reddy *et al*., 1989; Wium-Andersen and Andersen, 1972), it is still not known if variation among species in the quantity of oxygen transported correlates directly with variation in treatment ability.

The finding of higher levels of TDS, TSS and conductivity in vegetated troughs (over that found in unvegetated troughs) was unexpected. Increases in dissolved solids may have occurred from the release of acidic exudates from plant roots and/or the microbial release of ions upon decomposition of dead plant roots. The increases in TSS might have resulted from the mechanical disruption of the biofilm around the gravel particles by growing plant roots. However, it is also possible that the apparent increases in total dissolved and suspended solids were artifacts of increased plant transpiration acting to reduce water volume (not measured), resulting in a more concentrated effluent. Gersberg *et al*. (1984) found no differences in TSS between vegetated and unvegetated beds, and concluded that TSS reduction was a purely physical process. While our data are only marginally significant, they suggest that the plant roots can directly or indirectly influence effluent concentrations.

The three species differed greatly in their abilities to facilitate the treatment processes (Table I). *Typha*'s more aggressive growth and colonizing ability has been cited as a reason to avoid its use in systems such as these, but it clearly reduced BOD, TKN, ammonia, phosphate, and fecal coliform concentrations in effluent compared to *Scirpus* and *Juncus*. These results are in contrast to those reported by Gersberg *et al*., 1984, who found far higher nitrogen removal efficiencies in *Scirpus* beds than in *Typha* beds. Their *Typha* plants were evidently stressed, however, yellowing after 2–3 months with many plants dead after 6 months, a result they tentatively associated with high ammonia-N levels. In contrast, our *Typha* growth was large and lush, without any sign of the toxic effects from the wastewater stream. We note that our influent ammonia-N levels were roughly half those reported in their paper, a reminder that species' treatment abilities may also vary with the specific chemical makeup of the influent stream. Further, longer term studies are needed to ascertain if denser, more mature stands of the other two species might rival *Typha* monocultures in treatment ability, or if species mixtures not including *Typha* can perform as well (Bastian and Hammer, 1993).

It has been suggested that a diversity of species might partition the rooting zone (Guntenspergen *et al*., 1989) both spatially and temporally, and that species mixtures might thus exceed monocultures in treatment ability. The species mixture had consistently greater effects on effluent quality than did either the *Scirpus* or *Juncus* monocultures (Table I). The species mixture also had a consistently greater effect on effluent quality than did *Typha* in monoculture, although in no case was the difference between these two treatments significant. However, in only 5 of 21 parameters measured (including unpublished data) did the *Typha* monoculture have the greater effect, fewer than would be expected by chance alone (binomial probability, $p < 0.05$). Thus these data suggest that the hypothesis of species mixtures having greater effects than monocultures may be correct, but it remains to be seen if a stable species mixture can be found that will significantly exceed *Typha* monocultures in treatment ability. Further, *Typha* was the apparent winner in competition and produced the largest biomass, suggesting that the treatment ability of the mixture troughs was disproportionately due to the *Typha* individuals within the mixture. However, as the *Typha* density in mixture was only 1/3 that of *Typha* monocultures (5 plants instead of 15), the *Scirpus* and *Juncus* plants evidently also made significant contributions to the total treatment provided by the mixture troughs.

3.2. Plant growth

The plant mortality which occurred during the winter is attributed to freezing of the above-ground troughs. These plant species survive and thrive in natural and artificial wetlands even in colder climates than found in West Virginia (Hammer, 1989; Jenssen *et al*., 1993; Maehlum *et al*., 1995). The mortality found here might not be expected had the troughs been installed below ground level reducing the potential for complete wetland freezing.

Trough depth affected some aspects of plant growth (Table II), but the differences are difficult to interpret. Some aspects of both *Scirpus* and *Typha* plant growth were greater in shallow troughs (greater number of tillers per plant and leaves per shoot, respectively, Table II lines H and J), but the lengths of the longest *Typha* leaves were shorter (lines E and K) and the number of *Scirpus* flowering tillers was significantly lower (line I). However, as these plant growth differences did not seem to affect wastewater treatment, they also do not appear to suggest any advantages to deeper troughs.

Many measurements demonstrated *Typha*'s competitive superiority, at least in these initial two years of establishment. In summer 1994, growth of both *Juncus* and *Scirpus* were reduced in competition with *Typha* (Table II, lines A and B), relative to growth in monoculture. For these two species, resources were evidently more limiting in mixture than in monoculture. Similarly, mean new leaf production by the Typha plants was greater in the mixture troughs (line C), and there was a trend ($p < 0.10$) for a greater number of new *Typha* shoots (line D). In summer 1995, *Juncus* growth was again lower in mixture (line F). *Scirpus* tiller production did not differ significantly (line G), but fewer flowering tillers were produced in mixture (line I). *Typha* leaf production (total per trough) did not significantly differ, but *Typha* leaves were longer (taller) in the monoculture troughs, further suggesting that intraspecific competition (in this case, for light) was a stronger force on *Typha* growth than was interspecific competition.

If the *Typha* stands were in fact more limited by intraspecific competition, further increases in treatment ability with greater stand maturity might not be expected. Two lines of evidence suggest that the *Typha* stands were approaching a maximum of growth and, presumably, treatment ability. First is the smaller maximum leaf length in the shallow troughs in both years (Table II, lines E and K). Perhaps the shallow troughs were becoming root bound, while a potential for further root growth remained in the deep troughs. Second is the observation of an unexpected growth pattern in the *Typha* monoculture troughs: plants located nearer the influent were taller than plants nearer the effluent pipe. The pattern was not noted in *Scirpus* nor in *Juncus*. The negative correlation between *Typha* plant height and distance from the inflow pipe was found for both deep and shallow troughs, but was statistically significant only for the shallow troughs ($p < 0.05$).

This pattern of declining vigor with increasing distance from the influent pipe has also been observed for *Typha* as well as for other species in some full-scale wetlands in current domestic use in West Virginia. Two hypotheses are suggested: (1) concentrations of some plant nutrient are declining along a gradient, limiting plant growth at the lower end, or (2) some plant toxin is increasing in concentration with time or distance. In our troughs, influent phosphate levels were low (1.28 ± 0.22 mg L^{-1}), effluent concentrations were significantly reduced by gravel alone (presumably through 'biofilm' formation), and significantly further reduced by plant uptake. The lowest phosphate levels were measured in the effluent from troughs with the plant mixture. These levels (0.19 ± 0.12 mg L^{-1}) may have been low enough to hinder plant growth, particularly if flow within the denser portions of the rooting systems was restricted. Alternative explanations include a micronutrient shortage, or increases in concentrations of a plant toxin. Gersberg *et al*. (1984) suggested that high ammonium concentrations in raw sewage were responsible for the yellowing and death of *Typha* plants in their systems over a 6-month period, but this mechanism would predict that plants nearer the influent end of the troughs would show greater effects, rather than the effluent end as we observed. Edwards *et al*. (1993) noted a decline in *Scirpus* growth with distance from the influent pipe, but did not suggest an explanation for the observed pattern. Further research to elucidate the mechanism(s) of this observed decline seems warranted.

4. Conclusions

Few studies have compared the abilities of different plant species to facilitate the various processes which result in successful treatment of domestic wastewater. Much further work is needed if we are to be able fully to understand the roles plants play in these systems, and to be able to prescribe plantings which optimize the treatment abilities of constructed wetlands. Our results demonstrate significant differences among plant species in the treatment of wastewater, and suggest that polycultures (species mixtures) may perform better than monocultures. While *Typha* was clearly superior in facilitating the treatment processes and was also the stronger competitor, its aggressive nature and aesthetic drawbacks have been cited as reasons to avoid its use in these systems. Further, in other environmental conditions, it has exhibited signs of stress, reduced growth, and reduced ability to facilitate treatment. Thus a series of replicated, many-species, long-term screening experiments is suggested to ascertain which other plant species and species mixtures may provide both stable and effective wastewater treatment.

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