

IMPACT OF MUNICIPAL WASTEWATER EFFLUENT ON SEED BANK RESPONSE AND SOILS EXCAVATED FROM A WETLAND IMPOUNDMENT

Raymond G. Finocchiaro^{1,4}, Robert J. Kremer^{1,2}, and Leigh H. Fredrickson³

¹*Department of Soil, Environmental and Atmospheric Sciences
University of Missouri-Columbia
ABNR Building, Room 302, Columbia, Missouri, USA 65211*

²*USDA-ARS Cropping Systems and Water Quality Unit
Columbia, Missouri, USA 65211*

³*Wetland Management and Educational Services, Inc., Puxico, Missouri, USA 63960*

⁴*Present address:*

*U.S. Geological Survey, Northern Prairie Wildlife Research Center
8711 37th Street Southeast, Jamestown, North Dakota, USA 58401
E-mail: rfinocchiaro@usgs.gov*

Abstract: Intensive management of wetlands to improve wildlife habitat typically includes the manipulation of water depth, duration, and timing to promote desired vegetation communities. Increased societal, industrial, and agricultural demands for water may encourage the use of alternative sources such as wastewater effluents in managed wetlands. However, water quality is commonly overlooked as an influence on wetland soil seed banks and soils. In four separate greenhouse trials conducted over a 2-yr period, we examined the effects of municipal wastewater effluent (WWE) on vegetation of wetland seed banks and soils excavated from a wildlife management area in Missouri, USA. We used microcosms filled with one of two soil materials and irrigated with WWE, Missouri River water, or deionized water to simulate moist-soil conditions. Vegetation that germinated from the soil seed bank was allowed to grow in microcosms for approximately 100 d. Vegetative taxa richness, plant density, and biomass were significantly reduced in WWE-irrigated soil materials compared with other water sources. Salinity and sodicity rapidly increased in WWE-irrigated microcosms and probably was responsible for inhibiting germination or interfering with seedling development. Our results indicate that irrigation with WWE promoted saline-sodic soil conditions, which alters the vegetation community by inhibiting germination or seedling development.

Key Words: Eagle Buffs Conservation Area, salinity, sodicity, wetland vegetation

INTRODUCTION

Intensive management of seasonal wetlands for wildlife habitat typically involves flooding and dewatering impoundments seasonally to stimulate development of desirable plant communities (e.g., seed-producing annuals) from soil seed banks. This practice, referred to as moist-soil management (Fredrickson and Taylor 1982), has been used to provide wildlife habitats on more than 80% of the national wildlife refuges (Havera et al. 1996). Traditional sources of water used for intensely managed wetlands are commonly diverted or pumped from rivers, reservoirs, or aquifer. However, the allocation burden on these sources continues to increase as demands from the public, industrial, and agricultural sectors intensifies (EPA 2002). Hence, alternative water sources are constantly being sought to augment traditional sources.

One alternative that has received considerable attention is wastewater effluent (WWE) from

municipal treatment facilities. Nitrogen (N) and phosphorous (P) concentrations tend to be greater in WWE compared to other wetland water sources (Kadlec 1981), which can benefit plant biomass and seed production (Mudroch and Capobianco 1979, Kadlec 1981, Finlayson et al. 1986). However, the use of WWE also poses potential risk because some constituents in wastewater may detrimentally affect ecological processes. Salts are of particular concern because WWE often contains elevated concentrations relative to traditional water sources used to manage wetlands (Toze 2005). High concentrations of Na (sodicity) can damage soil structure (Sumner and Naidu 1998), resulting in altered soil pore distribution, aeration, infiltration, and hydraulic conductivity, and may dissolve potentially toxic heavy metals from primary and secondary minerals. In addition, salinity also can influence plant community dynamics (Ayers 1951, Kantrud et al. 1989, Baskin and Baskin 1998). For many freshwa-

ter species, excess salinity can impair seed imbibition, germination, and reduce plant growth (Bliss et al. 1984, Pearce-Pinto et al. 1990, Mamo et al. 1996, Gul and Weber 1998, Khan and Ungar 1999). Although the inhibitory effects of salinity on seeds of some species (e.g., glycophytes, halophytes) can be reversed by exposure to less salinity (Ungar 1995, Khan and Ungar 1999), this is not true for all species. Ionic toxicity from salts (i.e., NaCl) may irreversibly impair seed viability (Macharia et al. 1995). Consequently, the repeated use of salt-laden water sources, such as WWE, in freshwater wetlands may ultimately contribute to less diverse vegetation communities (Brock et al. 2005).

The potential risks associated with WWE may be particularly relevant when wetlands are managed to promote moist-soil vegetation due to intensive water level manipulations. Given the popularity of this technique, we designed a greenhouse experiment to more fully evaluate the effect of WWE on soil chemistry and plant community dynamics. Soil materials for this experiment were obtained from a managed wetland complex that has augmented a traditional water source with WWE since the complex's inception in 1996. Our objective was to quantify the soil seed bank response in terms of vegetation richness, density, and biomass to irrigation with WWE. We hypothesize that irrigation with WWE will alter soil chemistry and induce stress to the soil seed bank thereby changing the plant community composition.

METHODS

Collection and Processing of Soil Seed Banks

Soil seed banks and soil materials for greenhouse microcosms were collected during August 1997 from Eagle Bluffs Conservation Area located 9.7 km southwest of Columbia, Missouri. Adjacent to the Missouri River, the 1,794-ha Eagle Bluffs Conservation Area includes 15 wetland impoundments (526 ha) managed for wildlife by the Missouri Department of Conservation. The primary water source for the wetland complex is WWE pumped through a pipeline originating from wastewater treatment wetlands operated by the city of Columbia. Input of this water onto Eagle Bluffs Conservation Area is achieved through a series of control structures. Water from the Missouri River serves as an additional source and can be pumped into Eagle Bluffs Conservation Area through the River Supply Channel that also functions as an impoundment. Water from both sources can be mixed to irrigate most impoundments. The River Supply Channel

was selected for collection of soil materials because it has never received WWE. Soil materials were collected when the River Supply Channel was dewatered and soil materials were accessible.

Based on a survey of the River Supply Channel, two surface soil materials (0–15 cm) were selected because they represented the most common surface textures in that impoundment. The soil textures of the materials as determined by particle size analysis (Day 1965) were loamy fine sand (Sarpy; mixed, mesic Typic Udipsamments) and silt loam (Blake; fine-silty, mixed, superactive, calcareous, mesic Aquic Udifluvents) (Young et al. 2003). Approximately 2,000 kg of each soil material was excavated from the surface to an approximate depth of 15 cm and stored under tarps for 2 to 3 days. Each soil material was mixed and screened through a 1.27-cm² hardware cloth to remove rocks and vegetative debris. Three 100-g samples of each soil material were collected for analyses before distribution into microcosms. Samples were air-dried, sieved, and stored at 4°C until processed for determination of electrical conductivity (EC), pH, and exchangeable bases. Electrical conductivity was determined using the 1:1 soil to water method at 25°C (Whitney 1998) and pH was measured using a combination pH-reference electrode in a 1:1 soil to water and salt solution (0.01 M CaCl₂) (SSL Methods 2004). Exchangeable Ca and Mg were determined by atomic absorption and exchangeable Na and K by flame-photometric (emission) methods (Perkin Elmer 560 AA Spectrophotometer). Exchangeable sodium percentage (ESP) was determined following methods described by Bohn et al. (2001).

For each soil material, we constructed 27 microcosms using plastic containers (91-cm length, 61-cm width, 20-cm height). Each microcosm consisted of a 5-cm base layer of clean gravel (5–20 mm dia.) followed by 15 cm (approximately 72 kg) of air-dried soil material. A fine-mesh nursery cloth was placed between the gravel and soil to prevent mixing of materials.

Water Sources

Microcosms for both soil materials were irrigated with one of three water sources: WWE, Missouri River water (MOR), or de-ionized water (DI). Based on water quality data collected from 1994–2001 (Richards 1999, Knowlton and Jones 2003, USGS Missouri River Water Quality Data Base 2006), WWE contained an average of five times more total N and total P, four times more sodium (Na), 12 times more chloride (Cl), and six times more potassium (K) than MOR water (Table 2). Electrical

Table 1. Start and end dates of each trial.

Trial	Start Date	End Date
1	August 1997	November 1997
2	April 1998	July 1998
3	August 1998	November 1998
4	April 1999	July 1999

conductivity and mean turbidity of WWE were approximately two and 13 times greater than MOR (respectively), whereas calcium (Ca) and magnesium (Mg) concentrations in WWE were slightly less than in MOR. Wastewater effluent was collected from the Columbia Wastewater Treatment Unit 3 and MOR water was collected from the river's channel at a location on Eagle Bluffs Conservation Area. De-ionized water was supplied in the greenhouse (Culligan Water Company, Unibed system). To decrease the likelihood of including seeds in water sources during collection, water was collected with a pump fitted with small-aperture screen (approximately 1.3 mm) and water was visually examined for plant material and other debris. However, the addition of seeds to the microcosms through the water sources during irrigation was possible.

Greenhouse Experiment

The experiment consisted of four trials that lasted approximately 100 d each, which allowed most species that germinated from the seed bank to mature (Table 1). Spring and summer trial start dates were used to simulate schedules of water manipulations (flooding and dewatering) commonly used on impoundments managed for wildlife.

Microcosms filled with one of two soil materials were randomly assigned to be irrigated with one of the three water sources, which yielded six soil-water combinations (i.e., treatments). Nine microcosm replicates of each treatment were established. Water sources assigned to microcosms were not changed for the duration of the experiment. A randomized complete block design was used to assign microcosms a position in one of nine rows of six mutually exclusive treatments in the greenhouse. Rows and microcosms within a row were equally spaced apart. This process was repeated for each trial. The greenhouse was temperature-controlled and located in Columbia, Missouri. Air temperature ranged from 20 to 28°C during spring trials (April–July) and 25 to 38°C during summer trials (August–November). During non-trial periods (December–March), temperature ranged from and 4.4 to 15°C. Artificial light sources were not used in the greenhouse and natural photoperiod ranged from 12 to 15 hrs of light during spring trials and 11 to 14 hrs during summer trials.

For all trials, microcosms were initially irrigated with assigned water source (i.e., WWE, MOR, or DI) to saturate soil and pond water approximately 5 cm above the soil surface. During each trial, subsequent irrigations were applied to maintain soil water content of microcosms at approximately 80% field capacity. To monitor soil water content, tensiometers connected to mercury manometers were installed in microcosms filled with loamy fine sand and electrical resistance sensors were installed in microcosms filled with silt loam. Based on soil water retention curves developed for each soil material using the pressure chamber method (Klute

Table 2. Chemical properties of water sources used to irrigate microcosms during trials. Means are shown with one standard deviation[†] (if available).

	Missouri River Water	Municipal Wastewater Effluent
Total N (mg L ⁻¹)	2.2 ± 0.9	10.7 ± 4.5
NO ₃ (mg L ⁻¹)	1.3 ± 0.6	2.0 ± 2.3
NH ₄ (mg L ⁻¹)	0.04 ± 0.06	5.0 ± 3.4
Total P (mg L ⁻¹)	0.4 ± 0.3	2.2 ± 0.6
Alkalinity (mg L ⁻¹)	164 ± 23	222 ± 25
Cl (mg L ⁻¹)	17.9 ± 5.2	215 ± 46
SO ₄ (mg L ⁻¹)	166 ± 42	109 ± 17
Ca (mg L ⁻¹)	64	55
Mg (mg L ⁻¹)	23	19
K (mg L ⁻¹)	6	35
Na (mg L ⁻¹)	42.9 ± 14	161 ± 36
pH	8.2 ± 0.22	8.19 ± 0.11
EC (mS cm ⁻¹)	0.67 ± 0.13	1.33 ± 0.19
Turbidity (NTU) [‡]	11.1	151.8

[†] Data sources: USGS 1998, Knowlton and Jones 2003, USGS Water Quality Data Base 2006.

[‡] Mean turbidity (M. F. Knowlton, University of Missouri-Columbia, unpublished data 2005).

Table 3. Continued.

Species (abbreviation)	Wetland Indicator ⁵	Salinity Tolerance [‡]	Deionized				Missouri River				Wastewater			
			Trial 2	Trial 3	Trial 4	Trial 3	Trial 2	Trial 3	Trial 4	Trial 2	Trial 3	Trial 4	Trial 2	Trial 3
<i>Lindernia anagallidea</i> (Michx.) Pennell (linana)	OBL	0	730	0	407	611	0	526	3	0	0	0	0	0
<i>Lippia lanceolata</i> Michx. (phylan) ^D	OBL	-	0	0	0	2	0	0	0	0	0	0	0	0
<i>Lolium</i> sp. (lolsp) ^{DW}	-	2	0	0	0	0	0	0	0	0	0	0	0	0
<i>Lysimachia nummularia</i> L. (lysnum) ^D	FACW	-	0	0	0	0	0	0	0	0	0	0	0	0
<i>Mollugo verticillata</i> L. (molver) [*]	FAC	-	73	947	201	12	314	32	1	29	11	0	0	0
<i>Panicum capillare</i> L. (pancep)	FAC	1-2	0	183	0	0	138	0	0	54	0	0	0	0
<i>Panicum dichotomiflorum</i> Michx. (pandic)	FAC-	2	970	0	343	528	0	281	293	0	52	0	0	0
<i>Panicum virgatum</i> L. (panvir) [*]	FAC+	2	81	23	4	125	74	13	44	37	0	0	0	0
<i>Paspalum</i> sp. (passpp)	-	-	0	0	0	1	0	0	0	0	0	0	0	0
<i>Phytolaccaceae americana</i> L. (phyame) [*]	FAC-	-	0	0	0	0	0	0	0	0	0	0	0	0
<i>Polygonum lapathifolium</i> L. (pollap) ^{DW}	FACW+	0	88	0	29	61	0	31	28	0	2	0	0	0
<i>Ranunculus sceleratus</i> L. (ransce) [*]	FACW+	1	17	2	24	16	0	40	11	0	55	0	0	0
<i>Ranunculus</i> sp. (ranspp) ^W	-	-	1	0	0	2	0	0	0	0	0	0	0	0
<i>Rorippa sessiliflora</i> (Nutt.) Hitchc. (rorses) [*]	OBL	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Rotala ranosior</i> (L.) Koehne (rottram) ^{*†}	OBL	0	660	129	12	192	29	62	25	0	0	0	0	0
<i>Rumex orbiculatus</i> Gray (rumorb)	OBL	-	6	6	14	1	3	1	2	1	1	1	1	1
<i>Setaria fabrei</i> Herm. (setfab)	FACU+	-	0	0	0	0	0	0	0	0	0	0	0	0
<i>Setaria viridis</i> (L.) Beauv. (setvir) [*]	-	-	5	0	0	6	0	0	12	0	1	0	0	0
<i>Solanum americanum</i> Mill. (solame)	FACU-	-	6	0	43	17	10	65	11	0	10	0	0	0
<i>Sorghum halpense</i> (L.) Pers. (sorhal) ^D	FACU	1	0	1	0	6	0	0	1	0	0	0	0	0
<i>Veronica peregrine</i> L. (verper)	FACW+	0	579	10	658	234	26	219	0	8	3	0	0	0
<i>Wisteria frutescens</i> L. (wisfru) ^D	NI	0	1	2	2	14	0	0	0	0	0	0	0	0
<i>Xanthium strumarium</i> L. (xanstr) [*]	FAC	-	0	0	1	3	0	0	0	0	0	0	0	0
Total number of dicots / taxa		35/51	26/34	17/26	20/29	26/36	17/25	19/28	16/25	11/20	9/16			

⁵ Wetland indicator status based on USDA, NRCS PLANTS database, National Plant Data Center, Baton Rouge, LA, USA.
[†] Salinity tolerance for many species may vary by salt type, life stage, population, duration of exposure, temperature, and other factors (Liefers and Shay 1983). Ratings are based on soil electrical conductivity (solution extract): none = 0-2 dS/m; low = 2.1-4.0 dS/m; medium = 4.1-8.0 dS/m; high > 8.0 dS/m (USDA, NRCS, 2008, Stewart and Kantrud 1972, Xiong and Zhu 2002).

^{*} Salinity tolerance estimated (Flynn et al. 1995).

1986), we irrigated the loamy fine sand and silt loam when soil water content was below 17% (15 kPa soil water tension) and 30% (20 kPa soil water tension), respectively. For all trials and periods in between trials microcosms were not drained. The closed design of the microcosms allowed us to simulate conditions that commonly develop from moist-soil practices, shallowly ponded soil, mud flats, and moist-soil, and evaluate irrigation of wetland soils that have a subsoil of slow permeability or may contain a restrictive layer (e.g., claypan), which impedes hydraulic conductivity and leaching. Water movement in the microcosms was primarily influenced by evaporation and transpiration, which permitted soluble and insoluble constituents in the water sources to accumulate.

Seed Bank Response to Water Sources. During trials, maturing seed heads of plants were covered with fine-mesh cloth or seeds were removed by hand to prevent seed rain on to the soil material. All removed seeds were included in biomass measurements. At the completion of each trial, mean density (plants m^{-2}) and biomass of both alive and senesced plants were recorded by species for each microcosm. Biomass was determined by harvesting all above- and below-ground vegetative parts, rinsing material to remove soil, oven-drying material at 60° C for three days, and weighing (± 0.1 g) (Cain and Castro 1959). To facilitate collection of belowground plant biomass and apply equal disturbance to all microcosms, soil material was turned-over and mixed with hand trowels during harvest. The soil surface was leveled after harvest and microcosms were not disturbed between trials. During trial one, plant density was only recorded for a few species (i.e., *Amaranthus tamariscinus*, *Ammannia coccinea*, *Echinochloa crus-galli*, *Polygonum lapathifolium*, and *Xanthium strumarium*). In subsequent trials, plant density was determined for all species. Vegetation was identified to genus, and species if possible, using Steyermark (1963) and Yatskievych (1999). During non-trial periods, germination in microcosms was minimized by ceasing all irrigation and during non-trial winter months, temperature in the greenhouse was lowered to approximately match the outside ambient temperature. Few plants germinated in between trials (< 10 plants/trial) and these were discarded and excluded from measurements.

Following completion of trial four, a 5-cm diameter core sample of soil material was extracted from each microcosm. Three randomly selected replicates of each treatment were combined to create a composite sample of approximately 100 g; therefore, each treatment was represented by three

composite soil samples. Composite samples formed after trial four were analyzed with methods previously described.

Statistical Analysis

Analysis of variance (ANOVA) was performed with soil material and water source as fixed factors blocked within rows of the greenhouse array. A repeated measures ANOVA model was applied using SAS 9.1 (SAS Institute 2002–03) procedure MIXED (mixed linear model) with taxa richness, plant density, and biomass as dependent variables. Because the design included both fixed effects (soil, water, and trial) and random effects (rows), the mixed linear model was selected. Exchangeable bases, EC, and pH of soil materials were analyzed with soil and water factors fixed and blocked within assigned rows of the greenhouse array. Because soil samples were composites of three replicates, each composite sample for a treatment was assigned a different row in order to block by row. In all analyses, $P \leq 0.05$ was considered significant. Fisher's protected Least Squares Means comparison tests were used to separate means following ANOVA results when main effects were significant (Milliken and Johnson 1984). Principle component analysis (PCA, based on a covariance matrix) was used to examine general relations among microcosms based on the composition of the plants that germinated (CANOCO version 4.5, ter Braak and Smilauer 2002). Biplots were created for each trial showing the microcosms for each water source as well as plant species vectors.

RESULTS

Seed Bank Response to Water Sources

We identified 51 plant taxa over all four trials (35 dicots and 16 monocots) of which several taxa are important waterfowl food sources and are intolerant to salinity (Table 3). Of the 51 taxa recorded, 48 occurred in DI, 48 in MOR, and 39 in WWE irrigated soil materials. Total taxa recorded during individual trials ranged from 30 to 38. Average taxa richness differed significantly among water sources ($F_{6,144} = 2.82$, $P = 0.0127$), but differences varied by trial and soil material. During trial one, taxa richness in WWE-irrigated silt loam microcosms was significantly less ($P < 0.0001$) than DI-irrigated silt loam, but similar in richness to MOR-irrigated silt loam (Figure 1). Taxa richness in loamy fine sand microcosms was similar among water sources. In all subsequent trials taxa richness of WWE-

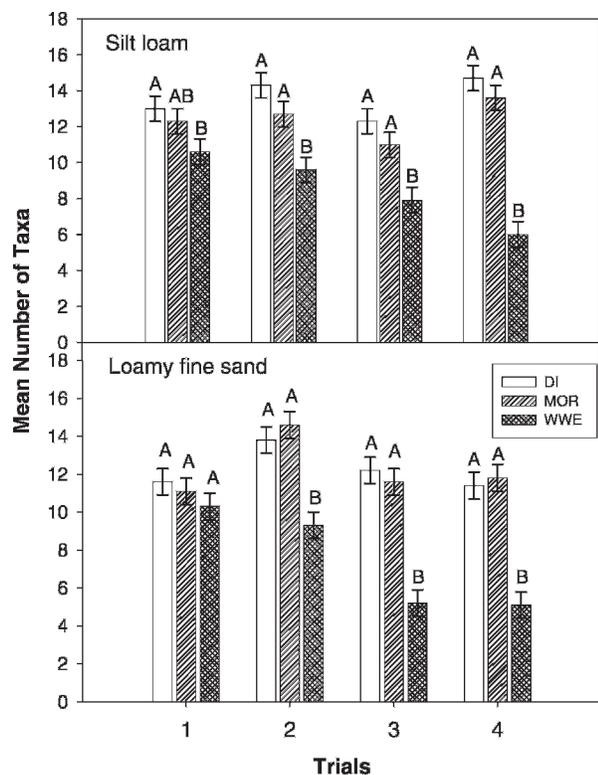


Figure 1. Number of plant taxa (Least-square means) by water source and trial for silt loam and loamy fine sand. Water sources were deionized (DI), Missouri River (MOR), and municipal wastewater effluent (WWE). Different letters above columns indicates significant differences ($P < 0.05$) among water sources in that trial. Vertical bars within a column represent one standard error.

irrigated microcosms was significantly less ($P < 0.0001$) than other water sources for either soil material.

Using presence and absence data, ordination results indicated that water source is related to plant species composition over time (Figure 2). In trial one, there were no grouping of microcosms based on plant communities that related to particular water source. All microcosms (water sources) were represented in all directions, indicating that plant communities were relatively similar among water sources. Composition of plant species occurring in WWE-irrigated microcosms started to differ from plant composition in DI- and MOR-irrigated microcosms in trial two and became more pronounced in subsequent trials. By trials three and four, WWE-irrigated microcosms were negatively correlated with most species vectors. In contrast, most species vectors were positively correlated with DI- and MOR-irrigated microcosms.

Irrigation with WWE also significantly reduced plant density compared with both DI- and MOR-

irrigated microcosms in the last three trials ($F_{4,96} = 4.65$, $P = 0.0018$; Figure 3A). Similarly, plant biomass was significantly less in WWE-irrigated microcosms than DI- or MOR- irrigated microcosms in trials three and four ($F_{6,144} = 8.50$, $P < 0.0001$; Figure 3B).

At the end of the last trial, concentrations of soil exchangeable Mg in microcosms differed among water sources ($F_{2,10} = 32.29$, $P < 0.0001$; Table 4) and was significantly less in the DI-irrigated microcosms than microcosms irrigated with either MOR or WWE ($P < 0.0001$). Exchangeable K in microcosms also differed among water sources ($F_{2,10} = 44.79$, $P < 0.0001$). Exchangeable K was significantly greater in the WWE-irrigated microcosms than either DI- or MOR-irrigated microcosms (both $P < 0.0001$). Microcosms of all water sources differed in exchangeable Na, EC, and ESP from each other ($F_{2,10} = 131.59$, $P < 0.0001$; $F_{2,10} = 159.51$, $P < 0.0001$; $F_{2,10} = 80.21$, $P < 0.0001$; respectively). WWE-irrigated microcosms had significantly greater exchangeable Na, EC, and ESP than microcosms irrigated with other water sources ($P < 0.0001$), and MOR-irrigated microcosms had significantly less of these three soil attributes ($P < 0.0103$, < 0.0060 , < 0.0017 , respectively). Exchangeable Ca and pH were similar among microcosms of all water sources.

DISCUSSION

Our study suggests that irrigation with WWE may not initially affect plant recruitment from the seed bank (i.e., trial one), but repeated exposure may eventually decrease the diversity of seeds that germinate and also affect plant density and biomass. Collectively, our results also suggest that changes in taxa richness, density, and biomass probably were the result of germination inhibition caused by increases in EC and ESP in the WWE-irrigated soil materials. Compared to MOR-irrigated microcosms, EC and ESP more than doubled in the soil materials irrigated with WWE. In fact, by the end of the experiment, WWE-irrigated materials had such substantial increases in EC and ESP that they were classified as saline-sodic (Havlin *et al.* 1999). Significant increases in soil salinity and sodicity can inhibit seed germination by restricting imbibition and causing Na and Cl ion toxicity (Bewely and Black 1982, Mansour 1994, Al-Karaki 2001). Sodium, in particular can be detrimental because, under certain conditions, Na can alter soil structure, thus impeding hydraulic conductivity, leaching, and root penetration (Oster 1982, Qadir *et al.*, 1996).

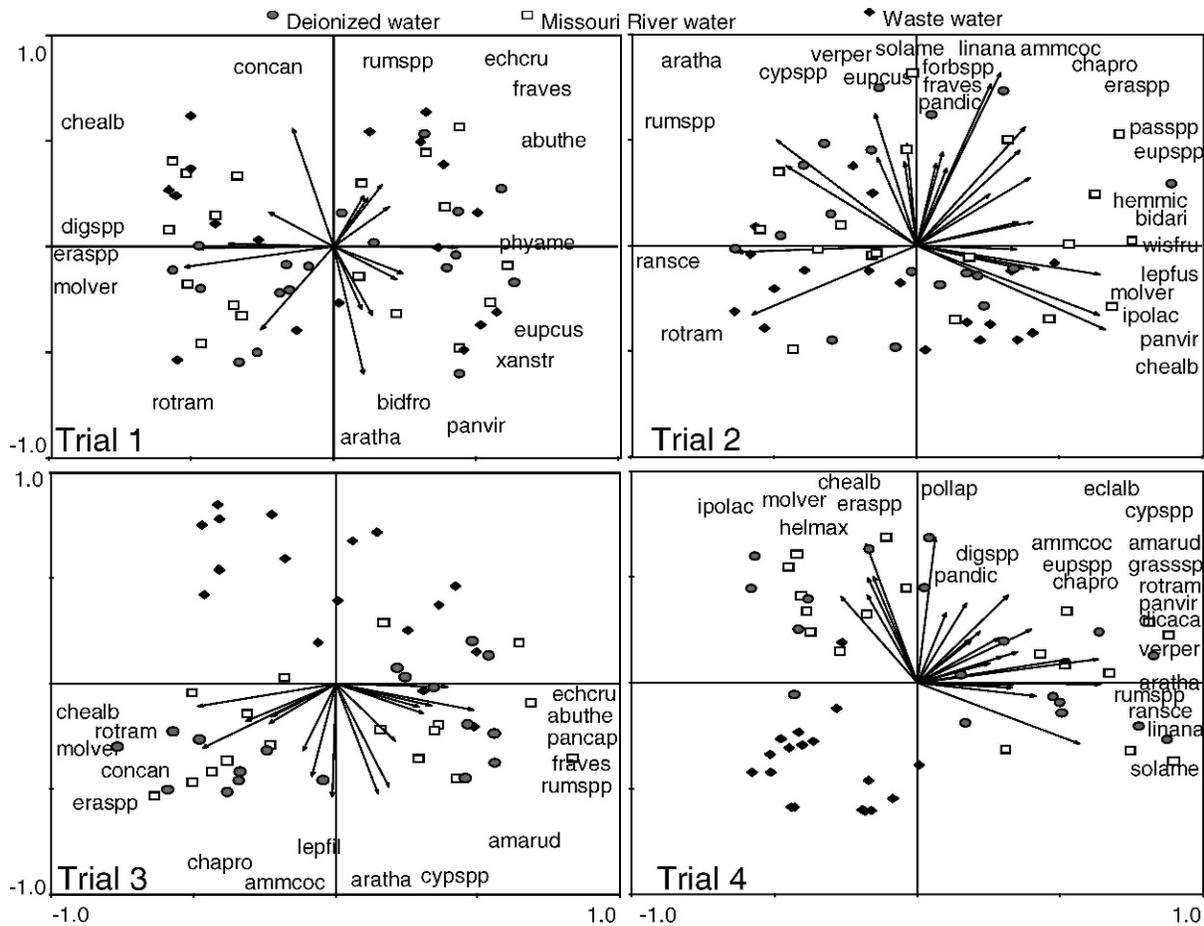


Figure 2. Biplots produced by principal components analysis of presence/absence data for species that germinated in microcosms during each trial. Microcosms were irrigated with deionized water (circles), Missouri River water (squares), or wastewater effluent (diamonds). Species vectors (arrows) point towards the corresponding species acronym, which are defined in Table 3. Species with a fit range of less than 10% were excluded from the biplots. Data are from 18 replicates of each water source regardless of soil material.

We compared EC of soils at Eagle Bluffs Conservation Area impoundments receiving WWE or MOR between 1998 and 2004. Over the six-year period, EC increased 59% ($0.76 \pm 0.17 \text{ mS cm}^{-1}$ to $1.21 \pm 0.23 \text{ mS cm}^{-1}$) in a WWE-irrigated impoundment and increased 25% ($0.68 \pm 0.41 \text{ mS cm}^{-1}$ to $0.85 \pm 0.13 \text{ mS cm}^{-1}$) in a MOR-irrigated impoundment. These measurements are substantially less than those measured in microcosms at the end of trial four. However, measurements of EC in impoundments were based on a general sampling scheme and were not focused on specific areas that may have subsoil stratigraphy and hydrology that could be more conducive to accumulation of salts. Additionally, several factors are involved such as precipitation and natural flood events that could affect the soils of these impoundments.

The inhibitory effect on germination induced by irrigation with WWE appeared to gradually affect a

wide variety of species in the seed banks regardless of their salinity tolerance. For example, *Chenopodium album*, *E. crus-galli*, and *Panicum virgatum*; which are intolerant to moderately-tolerant to salinity, respectively, ($0\text{--}8 \text{ dS m}^{-1}$; USDA-NRCS 2008, Rahman and Unger 1990), showed declines in abundances in almost all trials. Moreover, the highly salinity tolerant *Leptochloa fusca* (USDA-NRCS 2008) declined in WWE-irrigated microcosms, while abundance of this species increased in microcosm irrigated with DI or MOR. This wide-spread effect may impair the value of waterfowl habitat because approximately 50% of the germinated taxa from these seed banks are known waterfowl food sources.

From the biplots of each trial, and Table 3 it is possible to see that irrigation with WWE inhibited a wide variety of species regardless of salt tolerance or habitat preference (i.e., wetland indicator status). In trial two, a few taxa (i.e., *C. album*, *Cyperus* sp., *Ipomoea lacunose*, *L. fusca*, *Mollugo verticillata*, *P.*

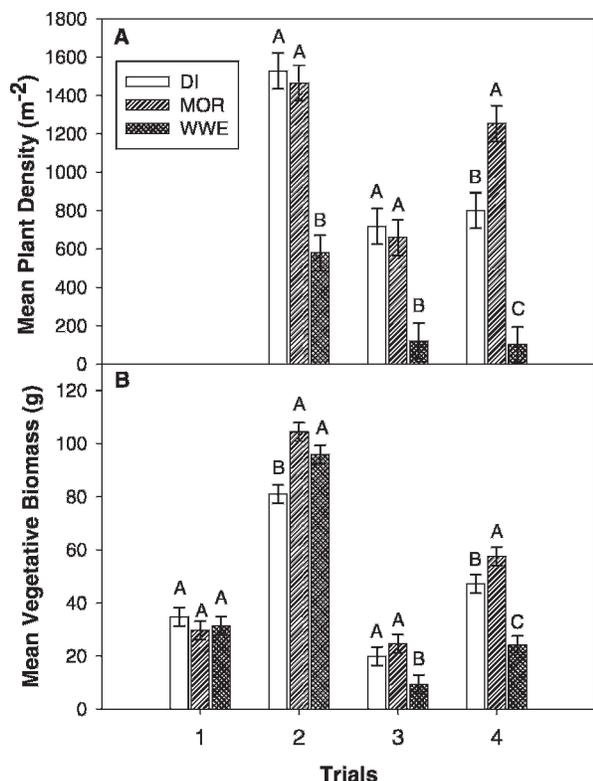


Figure 3. Least-squares means of plant density (A) and vegetative biomass (B) by water source and trial regardless of soil material. Water sources were deionized (DI), Missouri River (MOR), and municipal wastewater effluent (WWE). Plant density not record for all species in trial one therefore it was omitted. Different letters above columns indicates significant differences ($P < 0.05$) among water sources in that trial. Vertical bars within a column represent one standard error.

virgatum, *Ranunculus sceleratus*, and *Rotala ramosior*) were still positively correlated with WWE-irrigated microcosms. By trial four, no taxa were positively correlated with the majority of WWE-irrigated microcosms.

If the WWE-irrigated microcosms were leached of salts, it is likely that more seeds and species would germinate once the induced inhibitory effects

diminished. Several other workers have reported increased seed bank response after leaching; indicating that exposure to saline-sodic soil conditions did not irreversibly impair the viability of the seed banks (Walsh *et al.* 1991, Foderaro and Ungar 1997, DiTommaso 2004). Leaching also may influence germination and seedling development by removing germination-inhibiting compounds, such as abscisic acid from the seed coats (Wareing and Foda 1957, as cited in Baskin and Baskin 1998).

Some studies have reported greater salinity sensitivity in dicotyledous species than monocotyledous (Blanchard 2000, Davies *et al.* 2004). Results from these trials also suggest dicots in these soil seed banks may be more sensitive to soil salinity-sodicity than monocots. The WWE-irrigated microcosms had a greater overall net loss in the number of dicotyledous species (20%) across all trials than DI- (3.4%) or MOR-irrigated (6.1%) microcosms. In contrast, the number of monocotyledous species had an overall net gain for any water source.

Almost all species regardless of water source, decreased in species abundance as trials progressed. This was probably related to the use of the seed bank reserves without recruitment. Because seeds of maturing plants were kept from replenishing the seed banks, seed reserves declined over time. However, plant densities of more than 800 to 1300 (plants m⁻²) in DI- and MOR-irrigated microcosms (respectively) imply that abundance of viable seeds still persisted by the end of trial four, indicating that reserves were not depleted. Species diversity in the microcosms may have been restricted because collection of seed bank materials in August may have excluded species (i.e., transients) from the seed bank materials and therefore would not be represented in the vegetation composition.

CONCLUSION

Repeated irrigation with WWE on seed banks of soil materials excavated from wetlands at Eagle

Table 4. Mean Exchangeable bases, electrical conductivity (EC), exchangeable sodium percentage (ESP), and pH of both soil materials before start of trials (none) and after trial four that were irrigated with deionized water (DI), Missouri River water (MOR) or municipal wastewater effluent (WWE). Means (LS means \pm 1 SE) within columns followed by the same letter are not significantly different ($P > 0.05$).

Water Source	Exchangeable Bases (cmol kg ⁻¹)				EC (mS cm ⁻¹)	ESP (%)	pH(salt)
	Ca	Mg	K	Na			
none	25.9 \pm 8.8	3.2 \pm 1.6	0.3 \pm 0.14	0.2 \pm 0.1	0.2 \pm 0.0	0.64 \pm 0.3	7.2 \pm 0.0
DI	23.3 \pm 1.0 ^a	2.7 \pm 0.1 ^a	0.4 \pm 0.03 ^a	3.1 \pm 0.2 ^a	4.1 \pm 0.2 ^a	11.9 \pm 0.8 ^a	7.3 \pm 0.05 ^a
MOR	25.8 \pm 1.0 ^a	4.0 \pm 0.1 ^b	0.4 \pm 0.03 ^a	2.3 \pm 0.2 ^b	3.3 \pm 0.2 ^b	7.5 \pm 0.8 ^b	7.3 \pm 0.05 ^a
WWE	24.5 \pm 1.0 ^a	3.9 \pm 0.1 ^b	0.7 \pm 0.03 ^b	6.8 \pm 0.2 ^c	7.9 \pm 0.2 ^c	20.3 \pm 0.8 ^c	7.4 \pm 0.05 ^a

Bluffs Conservation Area decreased vegetative taxa richness, plant density and biomass. Seed germination and perhaps seedling development in WWE-irrigated soil materials was probably inhibited by the substantial increase in soil salinity and sodicity. Although these experiments were conducted in closed microcosms, which probably accelerated salt accumulation as water evaporated and vegetation transpired; irrigation with WWE escalated development of saline-sodic conditions relative to MOR as a water source and these soil conditions significantly impaired the vegetation community.

Wetland managers that employ moist-soil practices and use saline or sodic water sources on impoundments that contain seed banks comprised primarily of freshwater species may experience similar results. Irrigation with WWE on wetland impoundments that contain soils of slow permeability or with restrictive layers (e.g., pans) and not hydrologically connected to a freshwater source (e.g., ground water, flood water) may develop concentrations of salinity and sodicity that can alter composition of the vegetation communities. Elevated salinity and sodicity may adversely affect other wetland biotic systems such as the microbial community (Finocchiaro and Kremen 2009). Connection to freshwater and adequate drainage (especially when evaporation and transpiration is high) will likely prevent accumulation of Na and other salts from reaching detrimental concentrations in the soil.

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